SMITHSONIAN CONTRIBUTIONS TO KNOWLEDGE

PART OF VOLUME XXXIV

On the Construction of a Silvered Glass Telescope, Fifteen and a Half Inches in Aperture, and its Use in Celestial Photography

By HENRY DRAPER, M.D.

PROFESSOR OF NATURAL SCIENCE IN THE UNIVERSITY OF NEW YORK

(Reprinted from Vol. XIV, "Smithsonian Contributions to Knowledge," 1864)

AND

On the Modern Reflecting Telescope and the Making and Testing of Optical Mirrors

By GEORGE W. RITCHEY

ASSISTANT PROFESSOR OF PRACTICAL ASTRONOMY, AND SUPERINTENDENT OF INSTRUMENT CONSTRUCTION, IN YERKES OBSERVATORY

(No. 1459)

CITY OF WASHINGTON
PUBLISHED BY THE SMITHSONIAN INSTITUTION
1904

INTRODUCTION.

For few papers published by the Institution has there been a more constant demand than for the memoir by Professor Henry Draper, entitled "On the Construction of a Silvered Glass Telescope," originally issued forty years ago, in 1864.

The paper is of remarkable merit as a summary of, and an addition to, the knowledge existing at the time, but during the long interval which has elapsed, progress has been made in various directions and by various hands.

On the occasion of a new edition of this classic memoir, it was sought to give an account of the latest knowledge on the subject, and I was gratified to be able to obtain from Mr. Ritchey, whose labors in this direction are so well known, an account of the processes which he has employed for making the great mirrors that have been so effective at the Yerkes Observatory, and it has been decided to republish, with the original Draper memoir, but as an entirely independent contribution to the subject, the present article by Mr. Ritchey.

The great refracting instruments which have been produced in recent years have not superseded the use of the reflector, which, on the contrary, is occupying a more and more important place.

The reader is here presented with the most recent methods and results needed in the construction of great mirrors for modern reflecting telescopes.

S. P. Langley,

Secretary of the Smithsonian Institution.

Washington, June, 1904.

ON THE CONSTRUCTION

OF A

SILVERED GLASS TELESCOPE,

FIFTEEN AND A HALF INCHES IN APERTURE,

AND

ITS USE IN CELESTIAL PHOTOGRAPHY.

BY

HENRY DRAPER, M. D.,

PROFESSOR OF NATURAL SCIENCE IN THE UNIVERSITY OF NEW YORK.

COMMISSION

TO WHICH THIS PAPER HAS BEEN REFERRED.

Prof. Wolcott Gibbs.
Com. J. M. Gilliss, U. S. N.

Joseph Henry,
Secretary S. I.

CONTENTS.

AN ACCOUNT

OF

THE CONSTRUCTION AND USE OF A SILVERED GLASS TELESCOPE.

THE construction of a reflecting telescope capable of showing every celestial object now known, is not a very difficult task. It demands principally perseverance and careful observation of minutiæ. The cost of materials is but trifling compared with the result obtained, and I can see no reason why silvered glass instruments should not come into general use among amateurs. The future hopes of Astronomy lie in the multitude of observers, and in the concentration of the action of many minds. If what is written here should aid in the advance of that noble study, I shall feel amply repaid for my labor.

A short historical sketch of this telescope may not be uninteresting. In the summer of 1857, I visited Lord Rosse's great reflector, at Parsonstown, and, in addition to an inspection of the machinery for grinding and polishing, had an opportunity of seeing several celestial objects through it. On returning home, in 1858, I determined to construct a similar, though smaller instrument; which, however, should be larger than any in America, and be especially adapted for photography. Accordingly, in September of that year, a 15 inch speculum was cast, and a machine to work it made. In 1860, the observatory was built, by the village carpenter, from my own designs, at my father's country seat, and the telescope with its metal speculum mounted. This latter was, however, soon after abandoned, and silvered glass adopted. During 1861, the difficulties of grinding and polishing that are detailed in this account were met with, and the remedies for many of them ascertained. The experiments were conducted by the aid of three 15½ inch disks of glass, together with a variety of smaller pieces. Three mirrors of the same focal length and aperture are almost essential, for it not infrequently happens that two in succession will be so similar, that a third is required for attempting an advance beyond them. One of these was made to acquire a parabolic figure, and bore a power of 1,000. The winter was devoted to perfecting the art of silvering, and to the study of special photographic processes. A large portion of 1862 was spent with a regiment in a campaign in Virginia, and but few photographs were produced till autumn, when sand clocks and clepsydras of several kinds having been made, the driving mechanism attained great excellence. During the winter, the art of local corrections was acquired, and two 15½ inch mirrors, as well as two of 9 inches for the photographic enlarging apparatus, were completed. The greater part of 1863 has been occupied by lunar and planetary photography, and the enlargement of the small negatives obtained at the focus of the great reflector. Lunar negatives have been produced which have been magnified to 3 feet in

diameter. I have also finished two mirrors $15\frac{1}{2}$ inches in aperture, suitable for a Herschelian telescope, that is, which can only converge oblique pencils to a focus free from aberration. This work has all been accomplished in the intervals of professional labor.

The details of the preceding operations are arranged as follows: § 1. Grinding and Polishing the Mirrors; § 2. The Telescope Mounting; § 3. The Clock Movement; § 4. The Observatory; § 5. The Photographic Laboratory; § 6. The Photographic Enlarger.

§ 1. GRINDING AND POLISHING THE MIRRORS.

(1.) Experiments on a Metal Speculum.

My first 15 inch speculum was an alloy of copper and tin, in the proportions given by Lord Rosse. His general directions were closely followed, and the casting was very fine, free from pores, and of silvery whiteness. It was 2 inches thick, weighed 110 pounds, and was intended to be of 12 feet focal length. The grinding and polishing were conducted with the Rosse machine. Although a great amount of time was spent in various trials, extending over more than a year, a fine figure was never obtained—the principal obstacle to success being a tendency to polish in rings of different focal length. It must, however, be borne in mind that Lord Rosse had so thoroughly mastered the peculiarities of his machine as to produce with it the largest specula ever made and of very fine figure.

During these experiments there was occasion to grind out some imperfections, $\frac{8}{100}$ of an inch deep, from the face of the metal. This operation was greatly assisted by stopping up the defects with a thick alcoholic solution of Canada balsam, and having made a rim of wax around the edge of the mirror, pouring on nitro-hydrochloric acid, which quickly corroded away the uncovered spaces. Subsequently an increase in focal length of 15 inches was accomplished, by attacking the edge zones of the surface with the acid in graduated depths.

An attempt also was made to assist the tedious grinding operation by including the grinder and mirror in a Voltaic circuit, making the speculum the positive pole. By decomposing acidulated water between it and the grinder, and thereby oxidizing the tin and copper of the speculum, the operation was much facilitated, but the battery surface required was too great for common use. If a sufficient intensity was given to the current, speculum metal was transferred without oxidation to the grinder, and deposited in thin layers upon it. It was proposed at one time to make use of this fact, and coat a mirror of brass with a layer of speculum metal by electrotyping. The gain in lightness would be considerable.

During the winter of 1860 the speculum was split into two pieces, by the expansion in freezing of a few drops of water that had found their way into the supporting case.

(2.) Silvering Glass.

At Sir John Herschel's suggestion (given on the occasion of a visit that my father paid him in 1860), experiments were next commenced with silvered glass

specula. These were described as possessing great capabilities for astronomical purposes. They reflect more than 90 per cent. of the light that falls upon them, and only weigh one-eighth as much as specula of metal of equal aperture.

As no details of Steinheil's or Foucault's processes for silvering in the cold way were accessible at the time, trials extending at intervals over four months were made. A variety of reducing agents were used, and eventually good results obtained with milk sugar.

Soon after a description of the process resorted to by M. Foucault in his excellent experiments was procured. It consists in decomposing an alcoholic solution of ammonia and nitrate of silver by oil of cloves. The preparation of the solutions and putting them in a proper state of instability are very difficult, and the results by no means certain. The silver is apt to be soft and easily rubbed off, or of a leaden appearance. It is liable to become spotted from adherent particles of the solutions used in its preparation, and often when dissolved off a piece of glass with nitric acid leaves a reddish powder. Occasionally, however, the process gives excellent results.

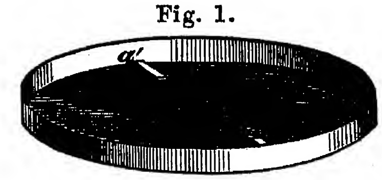
In the winter of 1861, M. Cimeg published his method of silvering looking-glasses by tartrate of potash and soda (Rochelle salt). Since I have made modifications in it fitting the silver for being polished on the reverse side, I have never on any occasion failed to secure bright, hard, and in every respect, perfect films.

The operation, which in many details resembles that of M. Foucault, is divided into: 1st, cleaning the glass; 2d, preparing the solutions; 3d, warming the glass; 4th, immersion in the silver solution and stay there; 5th, polishing. It should be carried on in a room warmed to 70° F. at least. The description is for a 15½ inch mirror.

1st. Clean the glass like a plate for collodion photography. Rub it thoroughly with nitric acid, and then wash it well in plenty of water, and set it on edge on filtering paper to dry. Then cover it with a mixture of alcohol and prepared chalk, and allow evaporation to take place. Rub it in succession with many pieces of cotton flannel. This leaves the surface almost chemically clean. Lately, instead of chalk I have used plain uniodized collodion, and polished with a freshly-washed piece of cotton flannel, as soon as the film had become semi-solid.

2d. Dissolve 560 grains of Rochelle salt in two or three ounces of water and filter. Dissolve 800 grains of nitrate of silver in four ounces of water. Take an ounce of strong ammonia of commerce, and add nitrate solution to it until a brown precipitate remains undissolved. Then add more ammonia and again nitrate of silver solution. This alternate addition is to be carefully continued until the silver solution is exhausted, when some of the brown precipitate should remain in suspension. The mixture then contains an undissolved excess of oxide of silver. Filter. Just before using, mix with the Rochelle salt solution, and add water enough to make 22 ounces.

Fig. 1.



The Silvering Vessel.

The vessel in which the silvering is to be performed may be a circular dish (Fig. 1) of ordinary tinplate, 16½ inches in diameter, with a flat bottom and perpendicular sides one inch high, and coated

inside with a mixture of beeswax and rosin (equal parts). At opposite ends of one diameter two narrow pieces of wood, a a', $\frac{1}{8}$ of an inch thick, are cemented. They are to keep the face of the mirror from the bottom of the vessel, and permit of a rocking motion being given to the glass. Before using such a vessel, it is necessary to touch any cracks that may have formed in the wax with a hot poker. A spirit lamp causes bubbles and holes through to the tin. The vessel too must always, especially if partly silvered, be cleaned with nitric acid and water, and left filled with cold water till needed. Instead of the above, India-rubber baths have been occasionally used.

3d. In order to secure fine and hard deposits in the shortest time and with weak solutions, it is desirable, though not necessary, to warm the glass slightly. This is best done by putting it in a tub or other suitably sized vessel, and pouring in water enough to cover the glass. Then hot water is gradually stirred in, till the mixture reaches 100° F. It is also advantageous to place the vessels containing the ingredients for the silvering solution in the same bath for a short time.

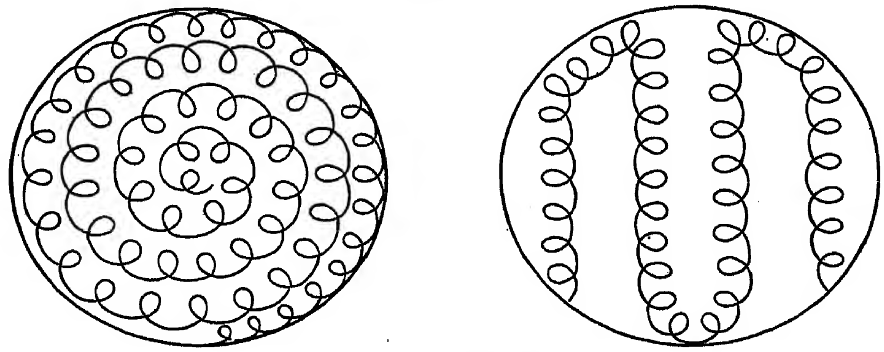
4th. On taking the glass out of the warm water, carry it to the silvering vessel—into which an assistant has just previously poured the mixed silvering solution—and immediately immerse it face downwards, dipping in first one edge and then quickly letting down the other till the face is horizontal. The back of course is not covered with the fluid. The same precautions are necessary to avoid streaks in silvering as in the case of putting a collodion plate in the bath. Place the whole apparatus before a window. Keep up a slow rocking motion of the glass, and watch for the appearance of the bright silver film. The solution quickly turns brown, and the silver soon after appears, usually in from three to five minutes. Leave the mirror in the liquid about six times as long. At the expiration of the twenty minutes or half hour lift it out, and look through it at some very bright object. If the object is scarcely visible, the silver surface must then be washed with plenty of water, and set on edge on bibulous paper to dry. If, on the contrary, it is too thin, put it quickly back, and leave it until thick enough. When polished the silver ought, if held between the eye and the sun, to show his disk of a light blue tint. On coming out of the bath the metallic surface should have a rosy golden color by reflected light.

5th. When the mirror is thoroughly dry, and no drops of water remain about the edges, lay it upon its back on a thoroughly dusted table. Take a piece of the softest thin buckskin, and stuff it loosely with cotton to make a rubber. Avoid using the edge pieces of a skin, as they are always hard and contain nodules of lime.

Go gently over the whole silver surface with this rubber in circular strokes, in order to commence the removal of the rosy golden film, and to condense the silver. Then having put some very fine rouge on a piece of buckskin laid flat on the table, impregnate the rubber with it. The best stroke for polishing is a motion in small circles, at times going gradually round on the mirror, at times across on the various chords (Fig. 2). At the end of an hour of continuous gentle rubbing, with occasional touches on the flat rouged skin, the surface will be polished so as to be perfectly black in oblique positions, and, with even moderate care, scratchless.

The process is like a burnishing. Put the rubber carefully away for another occasion.

Fig. 2.



Polishing Strokes.

The thickness of the silver thus deposited is about $\frac{1}{200,000}$ of an inch. Gold leaf, when equally transparent, is estimated at the same fraction. The actual value of the amount on a $15\frac{1}{2}$ inch mirror is not quite a cent – the weight being less than 4 grains (239 milligrammes on one occasion when the silver was unusually thick), if the directions above given are followed.

Variations in thickness of this film of silver on various parts of the face of the mirror are consequently only small fractions of $\frac{1}{200,000}$ of an inch, and are therefore of no optical moment whatever. If a glass has been properly silvered, and shows the sun of the same color and intensity through all parts of its surface, the most delicate optical tests will certainly fail to indicate any difference in figure between the silver and the glass underneath. The faintest peculiarities of local surface seen on the glass by the method of M. Foucault, will be reproduced on the silver.

The durability of these silver films varies, depending on the circumstances under which they are placed, and the method of preparation. Sulphuretted hydrogen tarnishes them quickly. Drops of water may split the silver off. Under certain circumstances, too, minute fissures will spread all over the surface of the silver, and it will apparently lose its adhesion to the glass. This phenomenon seems to be connected with a continued exposure to dampness, and is avoided by grinding the edge of the concave mirror flat, and keeping it covered when not in use with a sheet of flat plate glass. Heat seems to have no prejudicial effect, though it might have been supposed that the difference in expansibility would have overcome the mutual adhesion.

Generally silvered mirrors are very enduring, and will bear polishing repeatedly, if previously dried by heat. I have some which have been used as diagonal reflectors in the Newtonian, and have been exposed during a large part of the day to the heat of the sun concentrated by the $15\frac{1}{2}$ inch mirror. These small mirrors are never covered, and yet the one now in the telescope has been there a year, and has had the dusty film—like that which accumulates on glass—polished off it a dozen times.

In order to guard against tarnishing, experiments were at first made in gilding silver films, but were abandoned when found to be unnecessary. A partial conversion of the silver film into a golden one, when it will resist sulphuretted hydrogen,

can be accomplished as follows: Take three grains of hyposulphite of soda, and dissolve it in an ounce of water. Add to it slowly a solution in water of one grain of chloride of gold. A lemon yellow liquid results, which eventually becomes clear. Immerse the silvered glass in it for twenty-four hours. An exchange will take place, and the film become yellowish. I have a piece of glass prepared in this way which remains unhurt in a box, where other pieces of plain silvered glass have changed some to yellow, some to blue, from exposure to coal gas.

I have also used silvered glass plates for daguerreotyping. They iodize beautifully if freshly polished, and owing probably to the absence of the usual copper alloy of silver plating, take impressions with very short exposures. The resulting picture has a rosy warmth, rarely seen in ordinary daguerreotypes. The only precaution necessary is in fixing to use an alcoholic solution of cyanide of potassium, instead of hyposulphite of soda dissolved in water. The latter has a tendency to split up the silver. The subsequent washing must be with diluted common alcohol.

Pictures obtained by this method will bear high magnifying powers without showing granulation. Unfortunately the exposure required for them in the telescope is six times as great as for a sensitive wet collodion, though the iodizing be carried to a lemon yellow, the bromizing to a rose red, and the plate be returned to the iodine.

(3.) Grinding and Polishing Glass.

Some of the facts stated in the following paragraphs, the result of numerous experiments, may not be new to practical opticians. I have had, however, to polish with my own hands more than a hundred mirrors of various sizes, from 19 inches to $\frac{1}{4}$ of an inch in diameter, and to experience very frequent failures for three years, before succeeding in producing large surfaces with certainty and quickly. It is well nigh impossible to obtain from opticians the practical minutiæ which are essential, and which they conceal even from each other. The long continued researches of Lord Rosse, Mr. Lassell, and M. Foucault are full of the most valuable facts, and have been of continual use.

The subject is divided into: a. The Peculiarities of Glass; b. Emery and Rouge; c. Tools of Iron, Lead and Pitch; d. Methods of Examining Surfaces; e. Machines.

a. *Peculiarities of Glass.*

Effects of Pressure.—It is generally supposed that glass is possessed of the power of resistance to compression and rigidity in a very marked manner. In the course of these experiments it has appeared that a sheet of it, even when very thick, can with difficulty be set on edge without bending so much as to be optically worthless. Fortunately in every disk of glass that I have tried, there is one diameter on either end of which it may stand without harm.

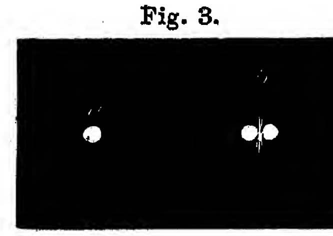
In examining lately various works on astronomy and optics, it appears that the same difficulty has been found not only in glass but also in speculum metal. Short used always to mark on the edge of the large mirrors of his Gregorian telescopes the point which should be placed uppermost, in case they were removed from their cells. In achromatics the image is very sensibly changed in sharpness if the flint

and crown are not in the best positions; and Mr. Airy, in mounting the Northumberland telescope, had to arrange the means for turning the lenses on their common axis, until the finest image was attained. In no account, however, have I found a critical statement of the exact nature of the deformation, the observers merely remarking that in some positions of the object glass there was a sharper image than in others.

Before I appreciated the facts now to be mentioned, many fine mirrors were condemned to be re-polished, which, had they been properly set in their mountings, would have operated excellently.

In attempting to ascertain the nature of deformations by pressure, many changes were made in the position of the disk of glass, and in the kind of support. Some square mirrors, too, were ground and polished. As an example of the final results, the following case is presented: A $15\frac{1}{2}$ inch unsilvered mirror $1\frac{1}{4}$ inch thick was set with its best diameter perpendicular, the axis of the mirror being horizontal (Fig. 8). The image of a pin-hole illuminated by a lamp was then observed to be single, sharply defined, and with interference rings surrounding it as at *a*, Fig. 3. On turning the glass 90 degrees, that is one quarter way round, its axis still pointing in the same direction, it could hardly be realized that the same concave surface was converging the rays. The image was separated into two of about equal intensity, as at *b*, with a wing of light going out above and below from the junction. Inside and outside of the focal plane the cone of rays had an elliptical section, the major axis being horizontal inside, and perpendicular outside. Turning the mirror still more round the image gradually improved, until the original diameter was perpendicular again—the end that had been the uppermost now being the lowest. A similar series of changes occurred in supporting the glass on various parts of the other semicircle. It might be supposed that irregularities on the edge of the glass disk, or in the supporting arc would account for the phenomena. But two facts dispose of the former of these hypotheses: in the first place if the glass be turned exactly half way round, the character of the image is unchanged, and it is not to be believed that in many different mirrors this could occur by chance coincidence. In the second place, one of these mirrors has been carefully examined after being ground and polished three times in succession, and on each occasion required the same diameter to be perpendicular. As to the second hypothesis no material difference is observed whether the supporting arc below be large or small, nor when it is replaced by a thin semicircle of tinplate lined with cotton wool.

Fig. 3.



Effect of Pressure on a Reflecting Surface.

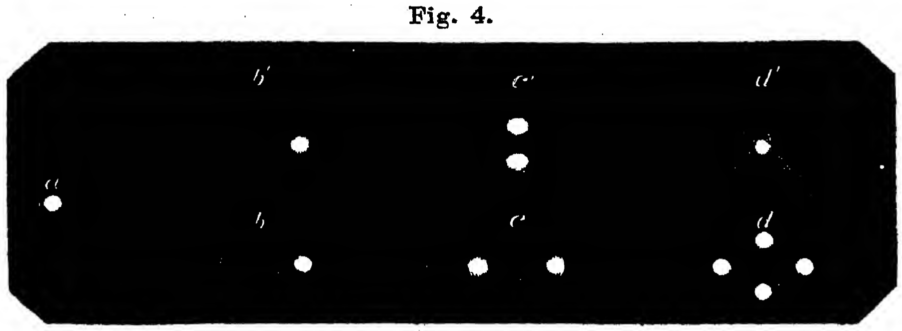
I am led to believe that this peculiarity results from the structural arrangement of the glass. The specimens that have served for these experiments have probably been subjected to a rolling operation when in a plastic state, in order to be reduced to a uniform thickness. Optical glass, which may be made by softening down irregular fragments into moulds at a temperature below that of fusion, may have the same difficulty, but whether it has a diameter of minimum compression can only be determined by experiment. Why speculum metal should have the same property might be ascertained by a critical examination of the process of casting,

and the effect of the position of the openings in the mould for the entrance of the molten metal.

Effects of Heat.—The preceding changes in glass when isolated appear very simple, and their remedy, to keep the proper diameter perpendicular, is so obvious that it may seem surprising that they should have given origin to any embarrassment. In fact it is now desirable to have a disk in which they are well marked. But in practice they are complicated in the most trying manner with variations produced by heat pervading the various parts of the glass unequally. The following case illustrates the effects of heat:—

A 15½ inch mirror, which was giving at its centre of curvature a very fine image (*a*, Fig. 4) of an illuminated pin-hole, was heated at the edge by placing the right

Fig. 4.



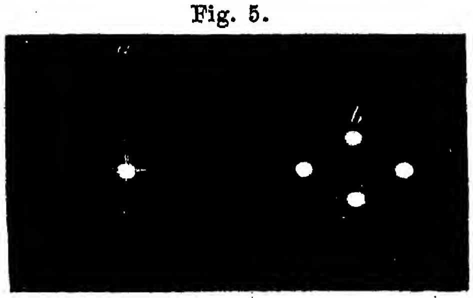
Effects of Heat on a Reflecting Surface.

hand on the back of the mirror, at one end of the horizontal diameter. In a few seconds an arc of light came out from the image as at *b′*, and on putting the left hand on the other extremity of the same diameter the appearance *c′* was that of two arcs of light crossing each other, and having an image at each intersection. The mirror did not recover its original condition in ten minutes. Another person on a subsequent occasion touching the ends of the perpendicular diameter at the same time that the horizontal were warmed, caused the image *d′* to become somewhat like two of *c′*, put at right angles to each other. A little distance outside the focus the complementary appearances, *b*, *c*, *d*, were found.

By unsymmetrical warming still more remarkable forms emerged in succession, some of which were more like certain nebulæ with their milky light, than any regular geometrical figure.

If the glass had, after one of these experiments, been immediately put on the polishing machine and re-polished, the changes in surface would to a certain extent have become permanent, as in Chinese specula, and the mirror would have required either re-grinding or prolonged polishing to get rid of them. This occurred unfortunately very frequently in the earlier stages of this series of experiments, and gave origin on one occasion to a surface which could only show the image of a pin-hole as a lozenge (*b*, Fig. 5), with an image at each angle inside the focus, and as an image *a* with four wings outside.

Fig. 5.



Effects of Heat rendered permanent.

But it must not be supposed that such apparent causes as these are required to

disturb a surface injuriously. Frequently mirrors in the process for correction of spherical aberration will change the quality of their images without any perceptible reason for the alteration. A current of cold or warm air, a gleam of sunlight, the close approach of some person, an unguarded touch, the application of cold water injudiciously will ruin the labor of days. The avoidance of these and similar causes requires personal experience, and the amateur can only be advised to use too much caution rather than too little.

Such accidents, too, teach a useful lesson in the management of a large telescope, never, for instance, to leave one-half the mirror or lens exposed to radiate into cold space, while the other half is covered by a comparatively warm dome. Under the head of the Sun-Camera, some further facts of this kind may be found.

Oblique Mirrors.—Still another propensity of glass and speculum metal must be noted. A truly spherical concave can only give an image free from distortion when it is so set that its optical axis points to the object and returns the image directly back towards it. But I have polished a large number of mirrors in which an image free from distortion was produced *only* when oblique pencils fell on the mirror, and the image was returned along a line forming an angle of from 2 to 3 degrees with the direction of the object. Such mirrors, though exactly suited for the Herschelian construction, will not officiate in a Newtonian unless the diagonal mirror be put enough out of centre in the tube, to compensate for the figure of the mirror. Some of the best photographs of the moon that have been produced in the observatory, were made when the diagonal mirror was 6 inches out of centre in the 16 inch tube. Of course the large mirror below was not perpendicular to the axis of the tube, but was inclined 2° 32′. The figure of such a concave might be explained by the supposition that it was as if cut out of a parabolic surface of twice the diameter, so that the vertex should be on the edge. But if the mirror was turned 180° it apparently did just as well as in the first position, the image of a round object being neither oval nor elliptical, and without wings. The image, however, is never quite as fine as in the usual kind of mirrors. The true explanation seems rather to be that the radius of curvature is greater along one of the diameters than along that at right angles. How it is possible for such a figure to arise during grinding and polishing is not easy to understand, unless it be granted that glass yields more to heat and compression in one direction than another.

After these facts had been laboriously ascertained, and the method of using such otherwise valueless mirrors put in practice as above stated, chance brought a letter of Maskelyne to my notice. He says, "I hit upon an extraordinary experiment which greatly improved the performance of the six-feet reflector" . . . . . It was one made by Short. "As a like management may improve many other telescopes, I shall here relate it: I removed the great speculum from the position it ought to hold perpendicular to the axis of the tube when the telescope is said to be rightly adjusted, to one a little inclined to the same and found a certain inclination of about 2½° (as I found by the alteration of objects in the finer one of Dollond's best night glasses with a field of 6°), which caused the telescope to show the object (a printed paper) incomparably better than before; insomuch that I could read many of the words which before I could make nothing at all of. It is plain, therefore, that this

telescope shows best with a certain oblique pencil of rays. Probably it will be found that this circumstance is by no means peculiar to this telescope." This very valuable observation has lain buried for eighty-two years, and ignorance of it has led to the destruction of many a valuable surface.

As regards the method of combating this tendency, it is as a general rule best to re-grind or rather re-fine the surface, for though pitch polishing has occasionally corrected it in a few minutes, it will not always do so. I have polished a surface for thirteen and a half hours, examining it frequently, without changing the obliquity in the slightest degree.

Glass, then, is a substance prone to change by heat and compression, and requiring to be handled with the utmost caution.

b. *Emery and Rouge.*

In order to excavate the concave depression in a piece of glass, emery as coarse as the head of a pin has been commonly used. This cuts rapidly, and is succeeded by finer grained varieties, till flour emery is reached. After that only washed emeries should be permitted. They are made by an elutriating process invented by Dr. Green.

Five pounds of the finest sifted flour emery are mixed with an ounce of pulverized gum arabic. Enough water to make the mass like treacle is then added, and the ingredients are thoroughly incorporated by the hand. They are put into a deep jar containing a gallon of water. After being stirred the fluid is allowed to come to rest, and the surface is skimmed. At the end of an hour the liquid containing extremely fine emery in suspension is decanted or drawn off with a siphon, nearly down to the level of the precipitated emery at the bottom, and set aside to subside in a tall vessel. When this has occurred, which will be in the lapse of a few hours, the fluid is to be carefully poured back into the first vessel, and the fine deposit in the second put into a stoppered bottle. In the same way by stirring up the precipitate again, emery that has been suspended 30, 10, 3, 1 minutes, and 20, 3, seconds is to be secured and preserved in wide-mouthed vessels.

The quantity of the finer emeries consumed in smoothing a 15½ inch surface is very trifling—a mass of each as large as two peas sufficing.

Rouge, or peroxide of iron, is better bought than prepared by the amateur. It is made by calcining sulphate of iron and washing the product in water. Three kinds are usually found in commerce: a very coarse variety containing the largest percentage of the cutting black oxide of iron, which will scratch glass like quartz; a very fine variety which can hardly polish glass, but is suitable for silver films; and one intermediate. Trial of several boxes is the best method of procuring that which is desired.

c. *Tools of Iron, Lead, and Pitch.*

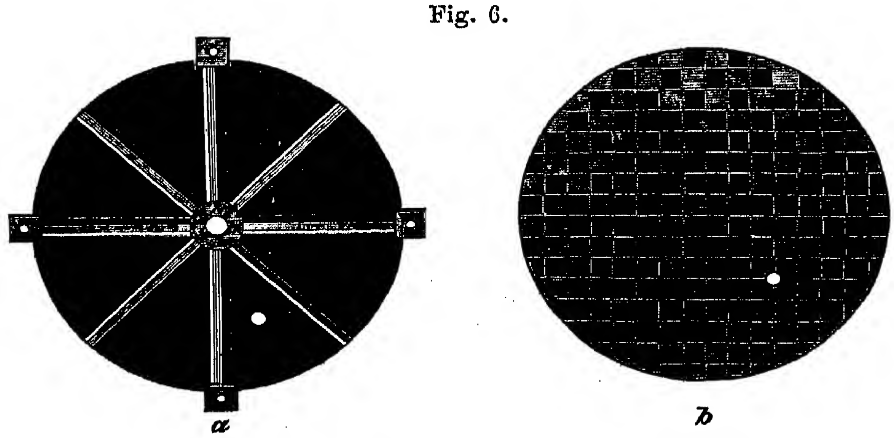
In making a mirror, one of the first steps is to describe upon two stout sheets of brass or iron, arcs of a circle with a radius equal to twice the desired focal length, and to secure, by filing and grinding them together, a concave and convex gauge. When the radius bar is very long, it may be hung against the side of a house. By

the assistance of these templets, the convex tools of lead and iron and the concave surface of the mirror are made parts of a sphere of proper diameter.

The excavation of a large flat disc of glass to a concave is best accomplished by means of a thick plate of lead, cast considerably more convex than the gauge. The central parts wear away very quickly, and when they become too flat must be made convex again by striking the lead on the back with a hammer. The glass is thus caused gradually to approach the right concavity. Ten or twelve hours usually suffice to complete this stage. The progress of the excavating is tested sufficiently well by setting the convex gauge on a diameter of the mirror, and observing how many slips of paper of a definite thickness will pass under the centre or edge, as the case may be. This avoids the necessity of a spherometer. The thickness of paper is found correctly enough by measuring a half ream, and dividing by the number of sheets. In this manner differences in the versed sine of a thousandth of an inch may be appreciated, and a close enough approximation to the desired focal length reached—the precision required in achromatics not being needed. The preparation of the iron tools on which the grinding is to be finished is very laborious where personal exertion is used. They require to be cast thin in order that they may be easily handled, and hence cannot be turned with very great exactness.

The pair for my large mirrors are $15\frac{1}{2}$ inches in diameter, and were cast $\frac{3}{8}$ of an inch thick, being strengthened however on the back by eight ribs $\frac{3}{4}$ of an inch high, radiating from a solid centre two inches in diameter (*a*, Fig. 6). They weighed 25

Fig. 6.



The Iron Grinder.

pounds apiece. Four ears, with a tapped hole in each, project at equal distances round the edge, and serve either as a means of attachment for a counterpoise lever, or as handles.

After these were turned and taken off the lathe chuck, they were found to be somewhat sprung, and had to be scraped and ground in the machine for a week before fitting properly. The slowness in grinding results from the emery becoming imbedded in the iron, and forming a surface as hard as adamant.

Once acquired, such grinders are very valuable, as they keep their focal length and figure apparently without change if carefully used, and only worked on glass of nearly similar curvature. At first no grooves were cut upon the face, for in the

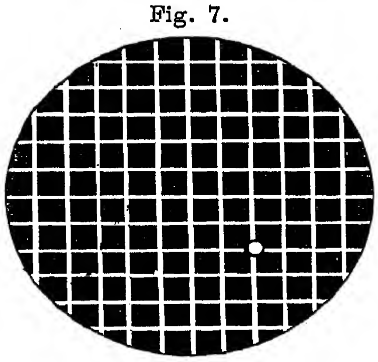
lead previously employed for fining they were found to be a fruitful source of scratches, on account of grains of emery imbedding in them, and gradually breaking loose as the lead wore away. Subsequently it appeared, that unless there was some means of spreading water and the grinding powders evenly, rings were likely to be produced on the mirror, and the iron was consequently treated as follows:—

A number of pieces of wax, such as is used in making artificial flowers, were procured. The convex iron was laid out in squares of $\frac{3}{4}$ of an inch on the side, and each alternate one being touched with a thick alcoholic solution of Canada balsam, a piece of wax of that size was put over it. This was found after many trials to be the best method of protecting some squares, and yet leaving others in the most suitable condition to be attacked. A rim of wax, melted with Canada balsam, was raised around the edge of the iron, and a pint of aqua regia poured in. In a short time this corroded out the uncovered parts to a sufficient depth, leaving an appearance like a chess-board, except that the projecting squares did not touch at the adjoining angles (*b*, Fig. 6). I should have chipped the cavities out, instead of dissolving them away, but for fear of changing the radius of curvature and breaking the thin plate. However as soon as the iron was cleaned, it proved to have become flatter, the radius of curvature having increased $7\frac{3}{4}$ inches. This shows what a state of tension and compression there must be in such a mass, when the removal of a film of metal $\frac{1}{50}$ of an inch thick, here and there, from one surface, causes so great a change.

When the glass has been brought to the finest possible grain on such a grinder, a polishing tool has to be prepared by covering the convex iron with either pitch or rosin. These substances have very similar properties, but the rosin by being clear affords an opportunity of seeing whether there are impurities, and therefore has been frequently used, straining being unnecessary. It is, however, too hard as it occurs in commerce, and requires to be softened with turpentine.

A mass sufficiently large to cover the iron $\frac{1}{8}$ of an inch thick is melted in a porcelain or metal capsule by a spirit lamp. When thoroughly liquid the lamp is blown out, and spirits of turpentine added, a drachm or two at a time. After each addition a chisel or some similar piece of metal is dipped into the fluid rosin, and then immersed in water at the temperature of the room. After a minute or two it is taken out, and tried with the thumb-nail. When the proper degree of softness is obtained, an indentation can be made by a moderate pressure.

Fig. 7.



The Polishing Tool.

The iron having been heated in hot water is then painted in stripes $\frac{1}{8}$ of an inch deep with this resinous composition. The glass concave to be polished being smeared with rouge, is pressed upon it to secure a fit, and the iron is then put in cold water. With a narrow chisel straight grooves are made, dividing the surface into squares of one inch, separated by intervals of one-quarter of an inch (Fig. 7). Under certain circumstances it is also desirable to take off every other square, or perhaps reduce the polishing surface irregularly here and there, to get an excess of action on some particular portion of the mirror.

It is well, on commencing to polish with a tool made in this way, to warm the glass as well as the tool in water (page 4) before bringing the two in contact. If this is not done the polishing will not go on kindly, a good adaptation not being secured for a length of time, and the glass surface being injured at the outset. The rosin on a polisher put away for a day or two suffers an internal change, a species of irregular swelling, and does not retain its original form. Heating, too, has a good effect in preventing disturbance by local variations of temperature in the glass.

The description of "Local Polishers" will be given under *Machines*.

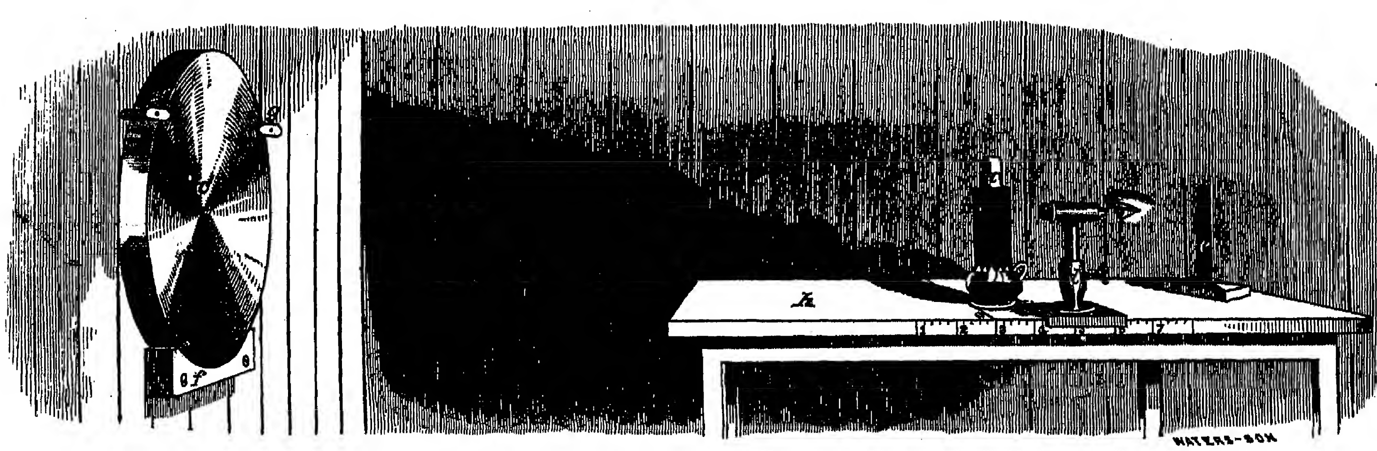
d. *Methods of Examining Surfaces.*

I have been in the habit of testing mirrors exclusively at the centre of curvature, not putting them in the telescope tube until nearly parabolic or finished. The means of trial are so excellent, the indications obtained so precise, and the freedom from atmospheric disturbances so complete, that the greatest facilities are offered for ascertaining the nature of a surface. In addition the observer is entirely independent of day or night, and of the weather. I do not think that anything more is learned of the telescope, even under favorable circumstances, than in the workshop. For the improvement of these methods of observation, Science is largely indebted to M. Foucault, whose third test—the second in the next paragraph—is sufficient to afford by itself a large part of the information required in correcting a concave surface.

There are two distinct modes of examination: 1st, observing with an eye-piece the image of an illuminated pin-hole at the focus, and the cone of rays inside and outside that plane; 2d, receiving the entire pencil of light coming from the mirror through the pupil on the retina, and noticing the distribution of light and shade, and the appearances in relief on the face of the mirror.

The arrangements for these tests are as follows: Around the flame of a lamp (*a*, Fig. 8) a sheet of tin is bent so as to form a cylindrical screen. Through it at the height of the brightest part of the flame, as at *b*, two holes are bored, a quarter of an inch apart, one $\frac{1}{32}$ of an inch in diameter, the other as small as the point of the finest needle will make—perhaps $\frac{1}{250}$ of an inch. This apparatus is to be set at the centre

Fig. 8.

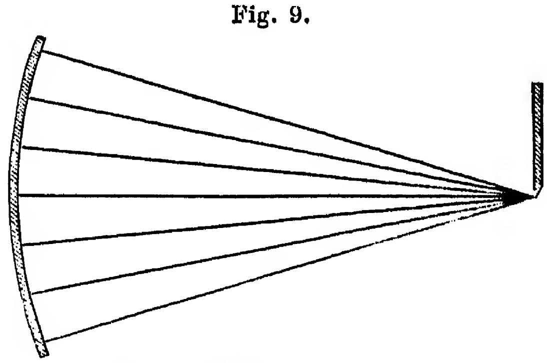


Testing a Concave at the Centre of Curvature.

of curvature of the mirror *c*—the optical axis of the latter being horizontal—and so adjusted that the light which diverges from the illuminated hole in use, may, after impinging on the concave surface of the glass, return to form an image close by the side of the tin screen. In the case of the first test, the returning rays are received into an eye-piece or microscope, *d*, magnifying 20 times, and moving upon a divided scale to and from the mirror. In the second test the eye-piece is removed away from before the eye, and a straight-edged opaque screen, *e*, is put in its place. The mirror is supported in these trials by an arc of wood *f*, lined with thick woollen stuff, and above two wooden latches, *g*, *g*, prevent it from from falling forward, but do not compress it. It is, of course, unsilvered. In the figure the table is represented very much closer to the mirror than it should be. In trials on the 15½ inch it has to be 25 feet distant.

The appearance that a truly spherical concave surface presents with the first test is: the image of the hole is sharply defined without any areola of aberration around it, and is surrounded by interference rings. Inside and outside the focus the cone of rays is exactly similar, and circular in section. It presents no trace of irregular illumination, nor any bright or dark circles. With the second test, when the eye is brought into such a position that it receives the whole pencil of reflected rays, and the opaque screen is gradually drawn across in front of the pupil, the brightness of the surface slowly diminishes, until just as the screen is cutting off the last relic of the cone of rays (Fig. 9), the mirror presents an uniform grayish tint, followed by total darkness, and gives to the eye the sensation of a plane.

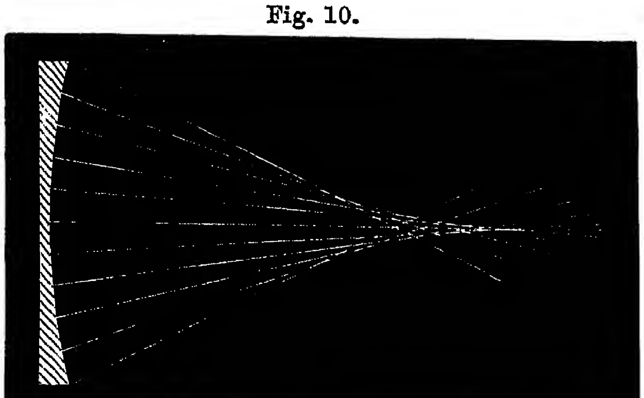
Fig. 9.



Action of the Opaque Screen.

If, however, the mirror is not spherical, but instead gradually *decreases* in focal length toward the edge, the following changes result: The image at the best focus is surrounded by a nebulosity, stronger as the deviation from the sphere is greater, and neither can a sharp focus be obtained nor interference fringes seen. In order to include this nebulosity in the image, it will be necessary to push the eye-piece toward the mirror. Before the cone of rays has completed its convergence, the mass of light will be seen to have accumulated at the periphery, and after the focus is past and divergence has commenced, the accumulation will be around the axis. That is, a caustic (Fig. 10) is formed with its summit from the mirror. By the second test, in gradually eclipsing the light coming from the mirror, just before all the rays are obstructed, a part of those which have constituted the nebulosity will escape past the screen (Fig. 11) into the eye, and cause there an extremely exaggerated appearance in relief of the solid superposed upon the

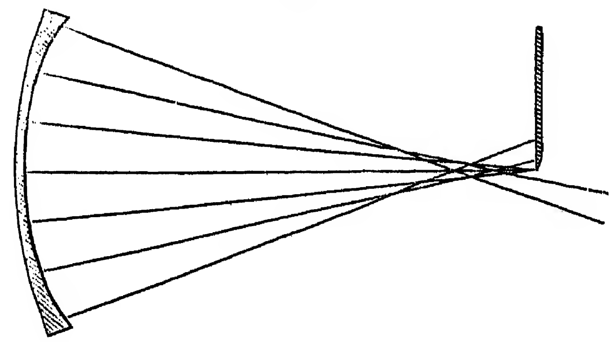
Fig. 10.



Caustic of Oblate Spheroidal Mirror.

true surface beneath. The glass will no longer seem to be a plane, but to have a section as in Fig. 12. Let us examine by the aid of M. Foucault's diagrams why it is that the surface seems thus curved. If the dotted line, Fig. 13, represents the section of the mirror, and the solid line a section of a spherical mirror of the same mean focal length, it will be seen that the curves touch at two points, but are separated by an interval elsewhere. If this interval be projected by means of the differences of the ordinates,

Fig. 11.



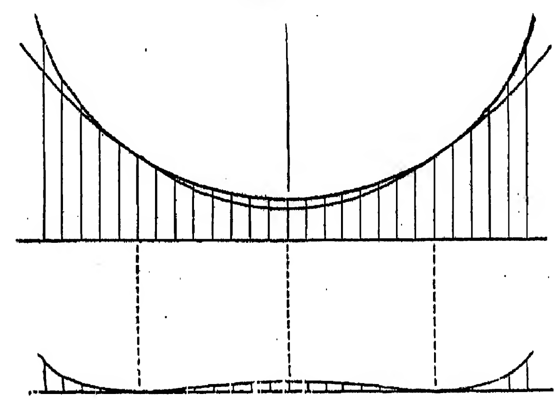
Action of the Opaque Screen.

Fig. 12.

Apparent Section of Oblate Spheroidal Mirror.

the resulting curve will be found to be the same as that which the mirror apparently has.

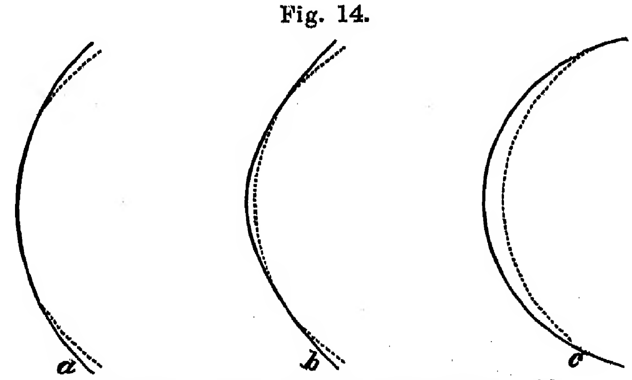
Fig. 13.



Section of Spherical and Spheroidal Mirrors.

If the opaque screen be drawn a short distance from the mirror, the appearance of the section curve will seem to change, the bottom of the groove (Fig. 12) between the centre and edge advancing inwards, and the mound in the middle growing smaller. If the screen be pushed toward the mirror the reverse takes place, the central mound becoming larger, but the edge decreasing. The reason for these variations becomes apparent by considering the three diagrams, Fig. 14. The dotted curve in each instance represents the real curve of the mirror described in the last paragraph, while the solid lines are circles drawn with radii progressionally shorter in *a*, *b* and *c*, and represent sections of three spherical mirrors whose focal lengths also progressively shorten.

Fig. 14.



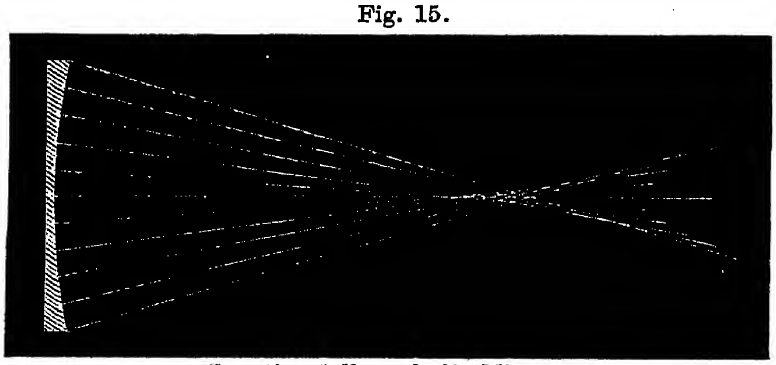
Relation of Spheres to Oblate Spheroid.

When the opaque screen is at a given distance from the mirror under examination, the only parts of the mirror which can officiate well are those which have a curvature corresponding to a radius equal to the same distance. All the other parts seem as if they were covered by projecting circular masses. In looking at Fig. 14, it is plain, then, if the opaque screen is at a maximum distance from the mirror, that the central parts alone will seem to operate, because the two curves (*a*) only touch there. If the screen is moved toward the mirror the curves (*b*) will coincide at some point between the centre and edge, while if carried still farther in only the edges touch and the appearance will be as if a

large mound were fixed upon the centre. I have been careful in explaining how a surface may thus seem to present entirely different characteristics if examined from points of view which vary slightly in distance, because a knowledge of these facts is of the utmost importance in correcting such an erroneous figure. It is now obvious that the correction will be equally effectual if the mirror be polished with a small rubber on the edge, or on the centre, or partly on each. The only difference in the result will be, that the mean focal length will be increased in the first instance, and decreased in the second, while it will remain unchanged in the third.

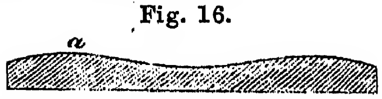
If the mirror, instead of having a section like that of an oblate spheroid, should have either an ellipse, parabola, or hyperbola, as its section curve, the appearances seen above are reversed. Whilst by the first test there is still an aberration round the image at the best focus, the eye-piece must now be drawn from the mirror to include it. The cone of rays is most dense round the axis inside, and at the periphery outside the focus, and the summit of the caustic (Fig. 15) is turned towards the mirror. The second test shows a section as in Fig. 16, a depression at the centre, and the edges turned backwards. The nature of the movement necessary to reduce the surface to a sphere is very plainly indicated, action on a zone *a* between the centre and edge. If, however, a parabolic section is required, the zone *a* must not be entirely removed, and the surface rendered apparently flat, but as much of it must be left as experience shows to be desirable.

Fig. 15.



Caustic of Hyperbolic Mirror.

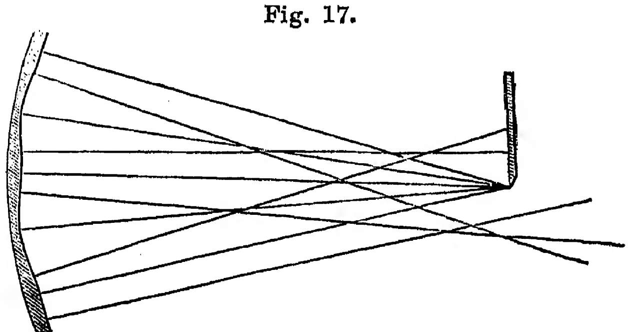
Fig. 16.



Apparent Section of Hyperbolic Mirror.

If, in still a fourth instance, the mirror is not formed by the revolution of any regular curve upon its axis, but has upon its surface zones of longer and shorter radius intermixed irregularly, a very common case, the two tests still indicate with precision the parts in fault, and the correction demanded. Thus the mirror seen in section in Fig. 17, when the principal mass of light was obstructed by the opaque screen, would still permit that coming from certain parts to find its way into the eye.

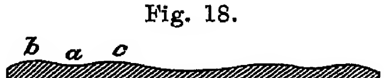
Fig. 17.



Action of the Opaque Screen.

Figure 18 represents an irregular mirror, that was produced in the process of correction of a hyperbolic surface, which had an apparent section like Fig. 16 previously. The zone *a* had been acted upon with a small local polisher, and the mirror was finished by subsequently softening down *b* and *c* with a larger tool.

Fig. 18.

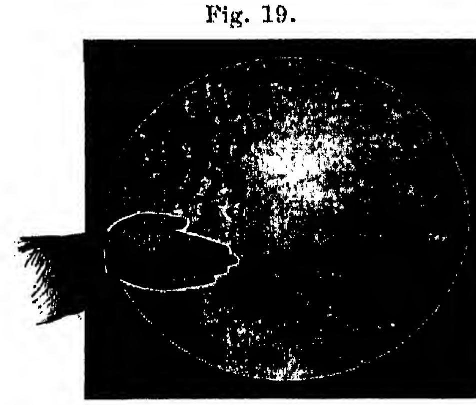


Apparent Section of Mirror with Rings.

After having gained from the preceding paragraphs a general idea of the value and nature of these tests at the centre of curvature, a more particular description of their use is desirable. M. Foucault in his methods first brings the mirror to a spherical surface, and then by moving the luminous pin-hole toward the mirror, and correspondingly retracting the eye-piece or opaque screen, carries it, avoiding aberration continually by polishing, through a series of ellipsoidal curvatures, advancing step by step toward the paraboloid of revolution. The length of the apartment, however, soon puts a termination to this gradual system of correction, and he is forced to perform the last steps of the conversion by an empirical process, and eventually to resort to trial in the telescope.

With my mirrors of 150 inches focal length, demanding from the outset a room more than 25 feet long, this successive system had to be abandoned. It was not found feasible to place the lamp in the distant focus of the ellipse—the workshop being less than 30 feet long—and putting the luminous source on stands outside, introduced several injurious complications, not the least of which was currents in the layers of variously refracting air in the apartment. In a still room the density and hygrometric variations in its various parts only give rise to slight embarrassment. The moment, however, that currents are produced, satisfactory examination of a mirror becomes difficult. The air is seen only too easily to move in great spiral convolutions between the mirror and the eye, areolæ of aberration appear around a previously excellent image, and were it not for the second test, any determination of surface would be impossible. By that test the real deviations from truth of figure can be distinguished from the atmospheric, and to a practised eye sufficient indications of necessary changes given. Such a movement as that caused by placing the hand in or under the line of the converging rays, will completely destroy the beauty of an image, and by the second test give origin in the first case to the appearance Fig. 19. In order to be completely exempt at all times from aërial difficulties, it is desirable to have control of a long underground apartment, the openings of which can be tightly closed. As no artificial warmth is needed, there is the minimum of movement in the inclosed air, and conclusions respecting a surface may be arrived at in a very short time. The mirror may also be supported from the ground, so that tremulous vibrations which weary the eye, and interfere with the accuracy of criticism, may be avoided.

Fig. 19.



Atmospheric Motions.

Driven then from observing an image kept continually free from aberration, through advancing ellipsoidal changes, it became necessary to study the gradual increase of deformation, produced by the greater and greater departures from a spherical surface, as the parabola was approached. It was found that a sufficient guide is still provided in these tests, by modifying them properly.

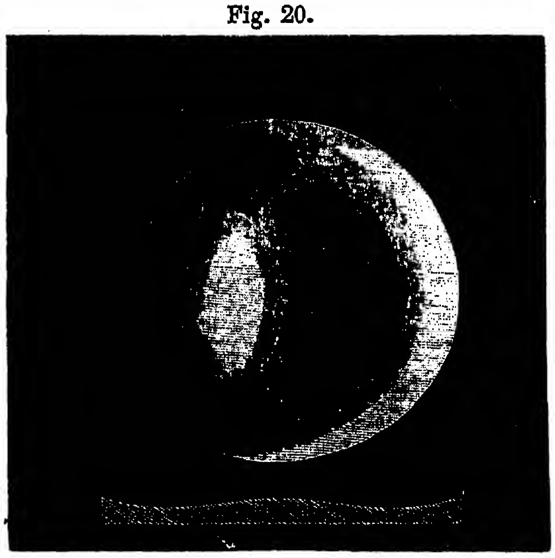
The longitudinal aberration of a mirror of small angular opening is easily calculated—being equal to the square of half the aperture, divided by eight times the

principal focal length. That is, if a $15\frac{1}{2}$ inch mirror of 150 inches focal length were spherical, and were used to converge parallel rays, those from its edge would reach a focus $\frac{5}{100}$ of an inch nearer the mirror than those from its central parts. If now the converse experiment be tried, and a mirror of the same size and focal length which can converge parallel rays, falling on all its parts, to one focus, be examined at the centre of curvature, it gives there an amount of longitudinal aberration $\frac{10}{100}$ of an inch, equal to twice the preceding. This latter, then, is the condition at the centre of curvature, to which such mirror must be brought in order to converge parallel rays with exactness. In addition, strict watch must be kept upon the zones intermediate between the centre and edge, both by measurement with diaphragms of their aberration, and better yet, by observation of the regularity of the curve of that apparent solid, Fig. 16, seen by the second test.

This modification of the first test is literally a method of parabolizing by measure, and is capable of great precision when the eye learns to estimate where the exact focus of a zone is. The little irregularities found round the edges of the holes through the tin screen, Fig. 8, are in this respect of material assistance. They show, too, the increased optical or penetrating power that is gained by increase of aperture. Minute peculiarities, not visible under very high powers with a 10 inch diaphragm, become immediately perceptible even with less magnifying when the whole aperture is used, provided the mirror is spherical.

In the use of the second test precautions have to be taken, as may be inferred from page 15, to set the opaque screen exactly in the proper position. The best method for ascertaining its location is, having received the image into the eye, placed purposely too near the mirror, to cause the screen to move across the cone of rays from the right towards the left side. A jet black shadow begins to advance at the same time, and in the same direction across the mirror. If the eye is then moved from the mirror sufficiently, this black shadow can be made to originate by the same motion of the screen as before, from the left or opposite side of the mirror. Midway between these extremes there is a point where the advance is from neither side. This is the true position for the screen when it is desired to see the imperfections of the surface in highly exaggerated relief, as in Fig. 20, which represents the appearance of Fig. 12.[1]

Fig. 20.



Adjusting the Opaque Screen.

The interpretation of the lights and shadows upon the face of a mirror in this test is always easy, and the observer is not likely to mistake an elevation for a depression, if he bears in mind the fact that the surface under

[1] In order to examine Fig. 20, the book should be held with the left side of the page toward a window or lamp. The eye should also be at least two feet distant. The centre will then be seen to protrude, and the surface present the apparent section engraved below it.

examination must always be regarded as illuminated by an oblique light coming from a source on the side opposite to that from which the screen advances, coming for instance from the left hand side, in the above description.

In practice, the diaphragms commonly used for a 15½ inch mirror have been as small as the light from the unsilvered surface would allow. A six inch aperture at the centre, a ring an inch wide round the edge, and a two inch zone midway between the two.

e. *Machines.*

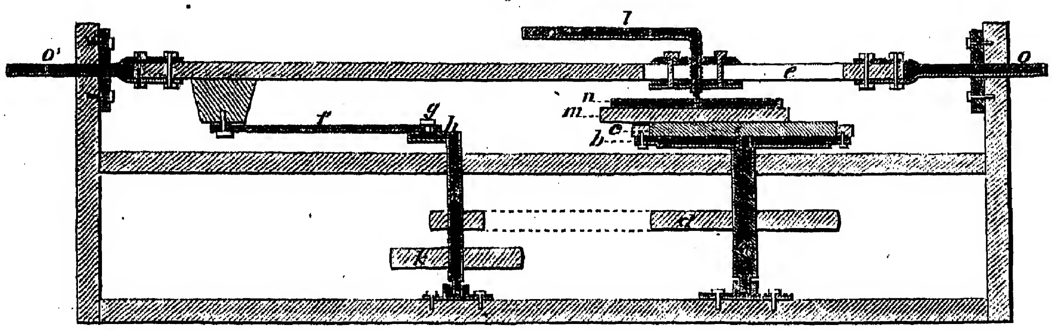
In the beginning of this section the difficulties into which I fell with Lord Rosse's machine were stated. These caused it at the time to be abandoned. A machine based on the same idea as Mr. Lassell's beautiful apparatus was next constructed. It varied, however, in this, that the hypocycloidal curve was described partly by the rotation of the mirror, and partly by the motions of the polisher—the axes of the spindles carrying the two being capable either of coincidence or lateral separation to a moderate extent. A great deal of time and labor was expended in grinding and polishing numerous mirrors with it, but still the difficulty that had been so annoying in the former machine persisted. Frequently, in fact generally, from six to eight zones of unequal focal length were visible, although on some occasions when the mirror was hyperbolic, the number was reduced to two. At first it was supposed that the fault lay with the polishing, the pitch accumulating irregularly from being of improper softness, for it was found to be particularly prone to heap up at the centre. But after I had introduced a method of fine grinding with elutriated hone powder, which enabled the glass to reflect light before the pitch polishing, it became evident that the zones were connected with the mode of motion of the mechanism. Many changes were made in the speed of its various elements, and a contrivance to control the irregular motion of the polisher introduced, but a really fine and uniform parabolic surface was never obtained, the very best showing when finished zones of different focal lengths. Although it cannot be said that I have tried this machine thoroughly, for Mr. Lassell has produced specula of exquisite defining power with it, and must have avoided these imperfections to a great extent, yet the evident necessity of complicating the movement[1] considerably, to avoid the polishing in rings, led me to adopt an entirely different construction, which was used until quite recently. Although it has now been replaced by another machine, which is still better in principle, and gives fine results much more quickly, yet as it produced one parabolic surface that bore a power of more than 1000, and as it serves to introduce the process of grinding, it is worthy of description. The action of machines for grinding and polishing has been thoroughly examined in my workshop, no less than seven different ones having been made at various times.

---

[1] Messrs. De La Rue and Nasmyth, who used one of Mr. Lassell's machines, as I have since learned, met with the same trouble, and were led to make two additions to the mechanism: 1, to control the rotation of the polisher rigorously; and 2, to give the whole speculum a lateral motion, by which the intersecting points of the curves described by the polisher were regularly changed in distance from the centre of the mirror. Mr. Lassell had previously, however, introduced a contrivance for this latter purpose himself.

The machine, which is a simplification of Lord Rosse's, was intended to give spiral strokes. It differed from the original, however, in demanding a changeable stroke, and in the absence of the lateral motion. In another most essential feature it varied from both that and Mr. Lassell's, *the mirror was always uppermost while polishing*, and being uncounterpoised escaped to as great an extent as possible from the effects of irregular pressure. To any one who has studied the deformations of a reflecting surface, and knows how troublesome it is to support a mirror properly, the advantage is apparent.

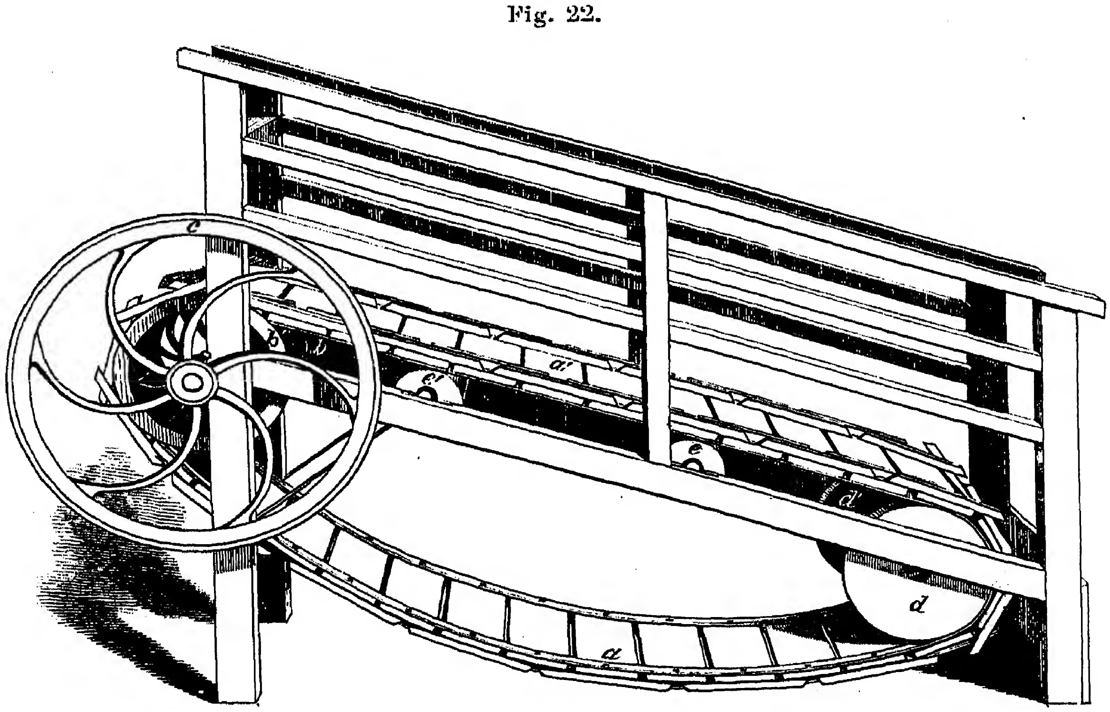
Fig. 21.



Polishing Machine.

The construction is as follows: A stout vertical shaft, *a*, Fig. 21, carries at its top a circular table *b*, upon which the polisher *c* is screwed. Below a band-wheel *d* is fixed. Above the table, at a distance of four inches, a horizontal bar *e* is arranged, so as to move back and forward in the direction of its length, and to carry with it by means of a screw *l*, the mirror *m*, and its iron back or chuck *n*. The bar is moved by a connecting rod *f*, attached to it at one end, and at the other to a pin *g*

Fig. 22.



The Foot Power.

moving a slot. This slot is in a crank *h*, carried by a vertical shaft *i*, near the former one *a*. The band-wheel *k* is connected with the foot power, Fig. 22. The

machine, except those parts liable to wear by friction, is made of wood. The ends $o\,o'$ of the horizontal bar e, are defended by brass tubes working in mahogany, and have even now but little shake, though many hundred thousands of reciprocations have been made.

The foot power consists of an endless band with wooden treads $a\,a'$, passing at one end of the apparatus over iron wheels $b\,b'$, which carry the band-wheel c upon their axle. At the other end it goes over the rollers $d\,d'$. Two pairs of intermediate wheels $e\,e'$, serve to sustain the weight of the man or animal working in it. The treads are so arranged that they interlock, and form a platform, which will not yield downwards. Owing to its inclination when a weight is put on the platform a', it immediately moves from b toward d and the band-wheel turns. By a moderate exertion, equivalent to walking up a slight incline at a slow rate, a power more than sufficient to polish a $15\frac{1}{2}$ inch mirror is obtained. This machine, in which very little force is lost in overcoming friction, is frequently employed for dairy use, and is moved commonly in the State of New York by a sheep. I have generally myself walked in the one used by me, and have travelled some days, during five hours, more than ten miles.

In order to give an idea of the method of using a grinding and polishing machine, the following extract from the workshop note-book is introduced:—

"A disk of plate glass $15\frac{1}{2}$ inches in diameter, and $1\frac{1}{4}$ inch thick was procured. It had been polished flat on both sides, so that its internal constitution might be seen.[1] It was fastened upon the table b of the machine, by four blocks of wood as at c, Fig. 21. Underneath the glass were three thick folds of blanket, 15 inches in diameter, to prevent scratching of the lower face, and avoid risk of fracture. A convex disk of lead weighing 40 pounds having been cast, was laid upon the upper surface of the glass, and then the screw l was depressed so as to catch in a perforated iron plate n, at the back of the lead m, and press downward strongly.

"Emery as coarse as the head of a pin having been introduced, through a hole in the lead, motion was commenced and continued for half an hour, an occasional supply of emery being given. The machine made 150 eight-inch cross strokes, and the mirror 50 revolutions per minute. The grinder m was occasionally restrained from turning by the hand. At the end of the time the detritus was washed away, and an examination with the gauge made. A spot 11 inches in diameter, and $\frac{1}{60}$ of an inch deep, was found to have been ground out. The same process was continued at intervals for ten hours, measurements with the gauge being frequently made. The concave was then sufficiently deep. The leaden grinder was kept of the right convexity by beating it on the back when necessary. A finer variety of coarse emery, and after that flour emery were next put on, each for an hour. These left the surface moderately smooth, and nearly of the right focal length. The leaden grinder was then dismissed, and the iron one, Fig. 6, put in its stead. The

[1] The glass that I have used has generally been such as was intended for dead-lights and sky-lights in ships.

mirror was removed from its place, and ground upon a large piece of flat glass for ten minutes, to produce a circular outline to the concavity. It was cemented with soft pitch to the concave iron disk, the counterpart of Fig. 6, and again recentred on the blanketed table *b*. Emeries of 3 and 20 seconds, and 1, 3, 10, 30, 60 minutes' elutriation were worked on it, an hour each. The rate of cross motion was reduced to 25 per minute to avoid heating, the mirror still revolving once for every three cross strokes. The screw pressure of *l* was stopped. This produced a surface exquisitely fine, semi-transparent, and appearing as if covered with a thin film of dried milk. It could reflect the light from objects outside the window until an incidence of 45 degrees was reached, and at night was found to be bright enough for a preliminary examination at the centre of curvature.

"The polisher was constructed in the usual way (page 12), and being smeared with rouge was fastened to the table *b*, where the mirror had been. The latter warmed in water to 120° F., was then put face downwards upon the former, and the screw *l* so lowered as to cause no pressure. The machine was allowed to make 20 four-inch cross strokes per minute, and the polisher to revolve once for every three strokes. The mirror being unconstrainedly supported on the polisher, was irregularly rotated by hand, or rather prevented from rotating with the polisher. The tendency of this method is to produce an almost spherical surface. To change it to a paraboloid, it was only necessary when the glass was polished all over to increase the length of the stroke to 8 inches, and continue working fifteen minutes at a time, examining in the intervals by the tests at the centre of curvature. The production of a polish all over occupied about two hours, but the correction of figure took more time, on account of the frequent examinations, and the absolute necessity of allowing the mirror to come back to a state of equilibrium from which it had been disturbed when worked on the machine." I have seen a mirror which was parabolic when just off the machine, by cooling over night become spherical. And these heat changes are often succeeded by other slower molecular movements, which continue to modify a surface for many days after.

This correction, where time and not length of stroke is the governing agent, has once or twice been accomplished in fifteen minutes, but sometimes has cost several hours. If the figure should have become a hyperboloid of revolution, that is, have its edge zones too long in comparison with the centre, it is only necessary to shorten the stroke to bring it back to the sphere, or even to overpass that and produce a surface in which at the centre of curvature the edge zones have too short a focal length (Fig. 12).

Very much less trouble from zones of unequal focal length was experienced after this machine and system of working were adopted. This was owing probably partly to the element of irregularity in the rotation of the mirror, and partly to the fact that the surface is kept spherical until polished, and is then rapidly changed to the paraboloid. Where the adjustments of an apparatus are made so as to attempt to keep a surface parabolic for some hours, there is a strong tendency for zones to appear, and of a width bearing a fixed relation to the stroke.

The method of producing reflecting surfaces next to be spoken of, is however that which has finally been adopted as the best of all, being capable of forming

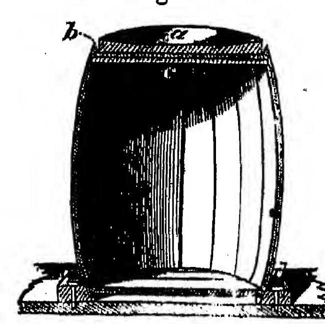
mirrors which are as perfect as can be, and yet only requiring a short time. It is the correction of a surface by local retouches. In the account published by M. Foucault, it appears that he is in France the inventor of this improvement.

The mode of practising the retouches is as follows: Several disks of wood, as *a*, Fig. 23, varying from 8 inches to ½ an inch in diameter, are to be provided, and covered with pitch or rosin of the usual hardness, in squares as at *c*, on one side.[1] On the other a low cylindrical handle *b* is to be fixed. The mirror *a*, Fig. 24, having been fined with the succession of emeries before described, is laid face upward on several folds of blanket, arranged upon a circular table, screwed to an isolated post in the centre of the apartment, which permits the operator to move completely round it. An ordinary barrel has generally supplied the place of the post, the head *c*, Fig. 24, serving for the circular table, and the rim *b* preventing the mirror sliding off. The other end is fastened to the floor by four cleets *d d'*.

Fig. 23.

Local Polisher.

Fig. 24.



Section of Optician's Post.

The large polisher is first moved over the surface in straight strokes upon every chord, and a moderate pressure is exerted. As soon as the mirror is at all brightened, perhaps in five minutes, the operation is to be suspended, and an examination at the centre of curvature made. By carefully turning round, the best diameter for support is to be found, and marked with a rat-tail file on the edge, and then the curve of the mirror ascertained. If it is nearly spherical, as will be the case if the grinding has been conducted with care and irregular heating avoided, it is to be replaced on the blanketed support, and the previous action kept up until a fine polish, free from dots like stippling, is attained. This stage should occupy three or four hours. Another examination should reveal the same appearances as the preceding. It is next necessary to lengthen the radius of curvature of the edge zones, or what is much better shorten that of the centre, so as to convert the section curve into a parabola. This is accomplished by straight strokes across every diameter of the face, at first with a 4 inch, then with a 6 inch, and finally with the 8 inch polisher. Examinations must, however, be made every five or ten minutes, to determine how much lateral departure from a direct diametrical stroke is necessary, to render the curve uniform out to the edge. Care must be taken always to warm the polisher, either in front of a fire or over a spirit lamp, before using it.

Perhaps the most striking feature in this operation is that the mirror presents continually a curve of revolution, and is not diversified with undulations like a ruffle. By walking steadily round the support, on the top of which the mirror is placed, there seems to be no tendency for such irregularities to arise.

If the correction for spherical aberration should have proceeded too far, and the mirror become hyperbolic, the sphere can be recovered by working a succession

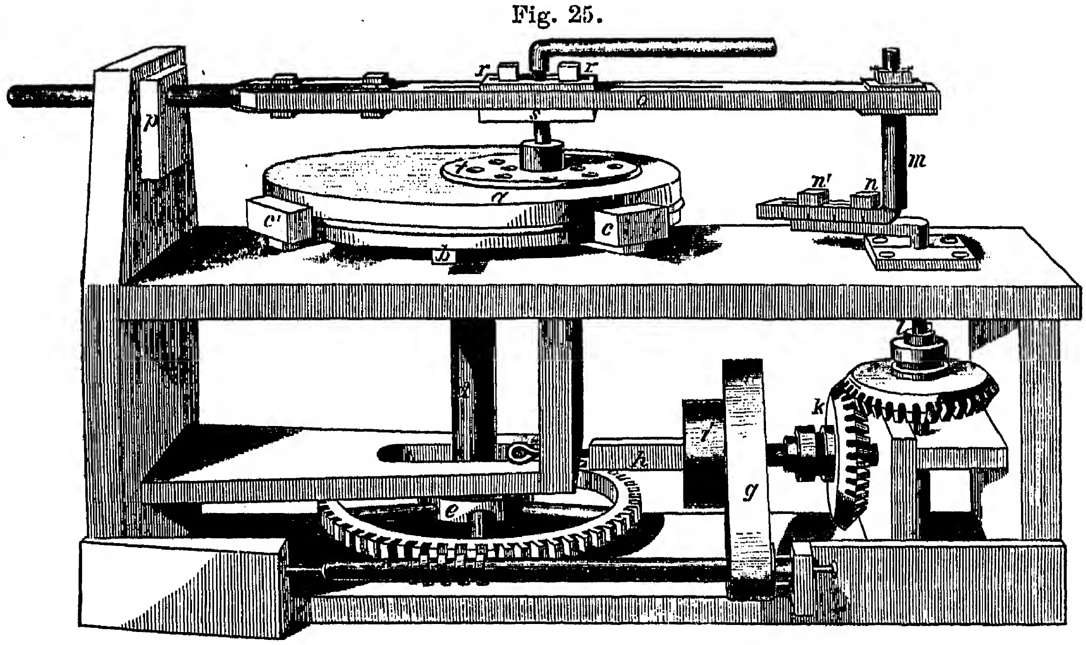
[1] M. Foucault used plano-convex lenses of glass, of a radius of curvature slightly less than that of the mirror, and covered with paper on the convex face.

of polishers of increasing size on the zone *a*, Fig. 16, intermediate between the centre and edge, causing their centres to pass along every chord that can be described tangent to the zone.

A most perfect and rapid control can thus be exercised over a surface, and an uniform result very quickly attained. It becomes a pleasant and interesting occupation to produce a mirror. But two effects have presented themselves in this operation, which unfortunately bar the way to the very best results. In the first place the edge parts of such mirrors, for more than half an inch all around, bend backwards and become of too great focal length, and the rays from these parts cannot be united with the rest forming the image. In the second place, the surface, when critically examined by the second test, is found to have a delicate wavy or fleecy appearance, not seen in machine polishing.[1] Although the variations from the true curve implied by these latter greatly exaggerated imperfections are exceedingly small, and do not prevent a thermometer bulb in the sunshine appearing like a disk surrounded by rings of interference, yet they must divert some undulations from their proper direction, or else they would not be visible. All kinds of strokes have been tried, straight, sweeping circular, hypocycloidal, &c. without effecting their removal. M. Foucault, who used a paper polisher, also encountered them. Eventually they were imputed to the unequal pressure of the hand, and in consequence a machine to overcome the two above mentioned faults of manual correction was constructed.

The mirror *a*, is carried by an iron chuck or table *b*, covered with a triple

Fig. 25.



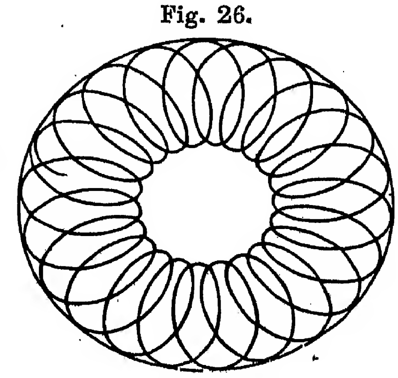
Machine for Local Corrections.

fold of blanket, and is prevented from slipping off by four cleets *c c'*. The vertical shaft *d* passes through a worm-wheel *e*, the endless screw of which *f*, is driven by a band *g*, from the primary shaft *h*. At *i* is the band-wheel for connection to

[1] By this it is not meant that there is a rippled polish, like that produced by buckskin.

the foot-power. At one end of the primary shaft is firmly fixed the cogwheel k, which drives the crank-shaft l. Attached to the horizontal part of l, is the crank-pin m. The two bolts $n\,n'$ move in a slot, so that the crank-pin may be set at any distance from 0 to 2 inches, out of line with l. Above, the crank-pin carries one end of the bar o, the other end passing through an elliptical hole in the oak-block p. Down the middle of the bar runs a long slot, through which the screw-pin q passes, and which permits q to be brought over any zone from the centre to the edge of the mirror a. It is retained by the bolts $r\,r'$, which are tapped into s. The local polisher is seen at t. The curve which the centre of the local polisher describes upon the face of the mirror, varies with the adjustments. Fig. 26 is a reduction from one traced by the machine, the overlapping being seen on the left side. The mirror is not tightly confined by the cleets $c\,c'$, for that would certainly injure the figure, but performs a slow motion of rotation, so that in no two successive strokes are the same parts of the edge pressed against them.

Fig. 26.



Hypocycloidal Curve.

The local polishers are made of lead, alloyed with a small proportion of antimony, and are 8, 6, and 4 inches in diameter, respectively. The largest and smallest are most used, the former on account of its size polishing most quickly, but the latter giving the truest surface. The rosin that covers them is just indentable by the thumb nail, and is arranged in a novel manner. The leaden basis, as seen at t, Fig. 25, is perforated in many places with holes, which permit evaporation, serve for the introduction of water where needed, and allow the rosin to spread freely. Grooves are made from one aperture to another, and the rosin thus divided into irregular portions. The effects of the production of heat are in this way avoided.

The mirror may be ground and fined on this machine, in the same manner as on that described at page 21, or it may be ground with a small tool 8 inches in diameter, as recently suggested by M. Foucault, the results in the latter case being just as good a surface of revolution as in the former. It is best polished with the 8 inch, and a moderate pressure may be given by the screw q, if the pitch is not too soft. This, however, tends to leave an excavated place at the centre of the mirror, the size depending on the stroke of the crank m, which should be about 2 inches. The pin q ought to be half way from the centre to the edge of the mirror, but must be occasionally moved right or left an inch along the slot. When the surface is approaching a perfect polish, the warmed 4 inch polisher must be put in the place of the 8 inch. The pin q must be set exactly half-way between the centre and edge of the mirror, and the crank must have a stroke of two inches radius. The polisher then just goes up to the centre of the glass surface with one edge, and to the periphery with the other, while the outer excursion of the inner edge and inner excursion of the outer edge meet, and neutralize one another at a midway point. Wherever the edge of a polisher changes direction many times in succession, on a surface, a zone is sure to form, unless avoided in this manner. All the foregoing description is for a $15\frac{1}{2}$ inch mirror.

By this system of local polishing the difficulties of heat, distribution of polishing powders, irregular contact of the rosin, &c. that render the attainment of a fine figure so uncertain usually, entirely disappear. A spherical surface is produced as above described, and afterwards by moving q towards the edge, and at the same time increasing the stroke, it is converted into a paraboloid. The fleecy appearance spoken of on a former page is not perceived, and the surface is good almost up to the extreme edge.

(4.) Eye-Pieces, Plane Mirrors and Test Objects.

The telescope is furnished with several eye-pieces of various construction, giving magnifying powers from 75 to 1200, or if it were desired even higher. For the medium powers 300 and 600 Ramsden, or rather positive eye-pieces have been adopted. They differ, however, from the usual form in being achromatic, that is, each plano-convex is composed of a flint and crown, arranged according to formulas calculated by Littrow. In this way a large flat field and absence of color are secured, and the fine images yielded by the mirror are not injured. For the higher powers, single achromatic lenses are used, and for the highest of all a Ross microscope.

With these means it has been found that the parabolic surfaces yielded by the processes before described, will define test objects excellently. Of close double stars they will separate such as γ^2 Andromedæ, and show the colors of the components. In the case of unequal stars which seem to be more severe tests, they can show the close companion of Sirius—discovered by Mr. Alvan Clark's magnificent refractor—the sixth component of θ^1 Orionis, and a multitude of other difficult objects.

As an example of light collecting power, Debillisima between ε and 5 Lyræ is found to be quintuple, as first noticed by Mr. Lassell. In the $18\frac{1}{2}$ inch specula of Herschel, it was only recorded as double, and, according to Admiral Smyth, Lord Rosse did not notice the fourth and fifth components. Jupiter's moons show with beautiful disks, and their difference in diameter is very marked. As for the body of that planet, it is literally covered with belts up to the poles. The bright and dark spots on Venus, and the fading illumination of her inner edge, and its irregularities are perceived even when the air is far from tranquil. Stars are often seen as disks, and without any wings or tails, unless indeed the mirror should be wrongly placed, so that the best diameter for support is not in the perpendicular plane, passing through the axis of the tube.

It has been found that no advantage other than the decrease of atmospheric influence on the image, results from cutting down the aperture of these mirrors by diaphragms, while the disadvantage of reducing the separating power, is perceived at the same time. Faint objects can be better seen with the whole surface than with a reduced aperture, and this though apparently a property common to all reflectors and object glasses is not so in reality. A defective edge will often cause the whole field to be filled with a pale milky light, which will extinguish the fainter stars. Good definition is just as important for faint as for close objects.

The properties of these mirrors have been best shown by the excellence of the

photographs taken with them. Although these are not as sharp as the image seen in the telescope, yet it must not be supposed that an imperfect mirror will give just as good pictures. A photograph which is magnified to 3 feet, represents a power of 380. As the original negative taken at the focus of the mirror is not quite 1½ inch in diameter when the moon is at its mean distance, it has to be enlarged about 25 times, and has therefore to be very sharp to bear it.

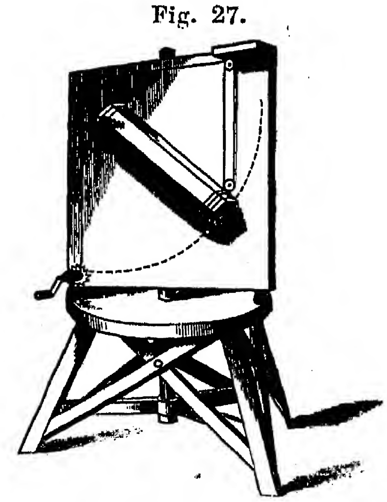
The light collecting power of an unsilvered mirror is quite surprising. With a 15½ inch, the companion of α Lyræ can be perceived, though it is only of the eleventh magnitude. The moon and other bright objects are seen with a purity highly pleasing to the eye, some parts being even more visible than after silvering.

In order to finish this description, one part more of the optical apparatus requires to be noticed—the plane mirrors. In the Newtonian reflector the image is rejected out at the side of the tube by a flat surface placed at 45° with the optical axis of the large concave.[1] If this secondary mirror is either convex or concave, it modifies the image injuriously, causing a star to look like a cross, and this though the curvature be so slight as hardly to be perceptible by ordinary means. For a long time I used a piece 3×5 inches, which was cut from the centre of a large looking-glass accidentally broken, but eventually found that by grinding three pieces of 6 inches in diameter against one another, and polishing them on very hard pitch, a nearer approach to a true plane could be made. They were tested by being put in the telescope, and observing whether the focus was lengthened or shortened, and also by trial on a star. When sufficiently good to bear these tests, a piece of the right size was cut out with a diamond, from the central parts.

§ 2. THE TELESCOPE MOUNTING.

The telescope is mounted as an altitude and azimuth instrument, but in a manner that causes it to differ from the usual instrument of that kind. The essential feature is, that *the eye-piece or place of the sensitive plate is stationary at all altitudes*, the observer always looking straight forward, and never having to stoop or assume inconvenient and constrained positions.

Fig. 27.



Miss Herschel's Telescope.

The stationary eye-piece mounting was first used by Miss Caroline Herschel, who had a 27 inch Newtonian arranged on that plan. Fig. 27. (Smyth's Celestial Cycle.)

Subsequently it was applied to a large telescope by Mr. Nasmyth, the eminent engineer, but no details of his construction have reached me. He used it for making drawings of the moon, which are said to be excellently executed.

When it became necessary to determine how my telescope should be mounted, I was strongly urged to make it

[1] A right-angled prism cannot be used with advantage to replace the plane silvered mirrors, because it transmits less light than they reflect, is more liable to injure the image, and the glass is apt to be more or less colored. Its great size and cost, one three inches square on two faces being required for my purposes, has also to be considered.

an equatorial. But after reflecting on the fact that it was intended for photography, and that absolute freedom from tremor was essential, a condition not attained in the equatorial when driven by a clock, and in addition that in the case of the moon rotation upon a polar axis does not suffice to counteract the motion in declination, I was led to adopt the other form.

A great many modifications of the original idea have been made. For instance, instead of counterpoising the end of the tube containing the mirror by extending the tube to a distance beyond the altitude or horizontal axis, I introduced a system of counterpoise levers which allows the telescope to work in a space little more than its own focal length across. This construction permits both ends of the tube to be supported, the lower one on a wire rope, and gives the greatest freedom from tremor, the parts coming quickly to rest after a movement. In the use of the telescope for photography, as we shall see, the system of bringing the mass of the instrument to complete rest before exposing the sensitive plate, and only driving that plate itself by a clock, is always adopted.

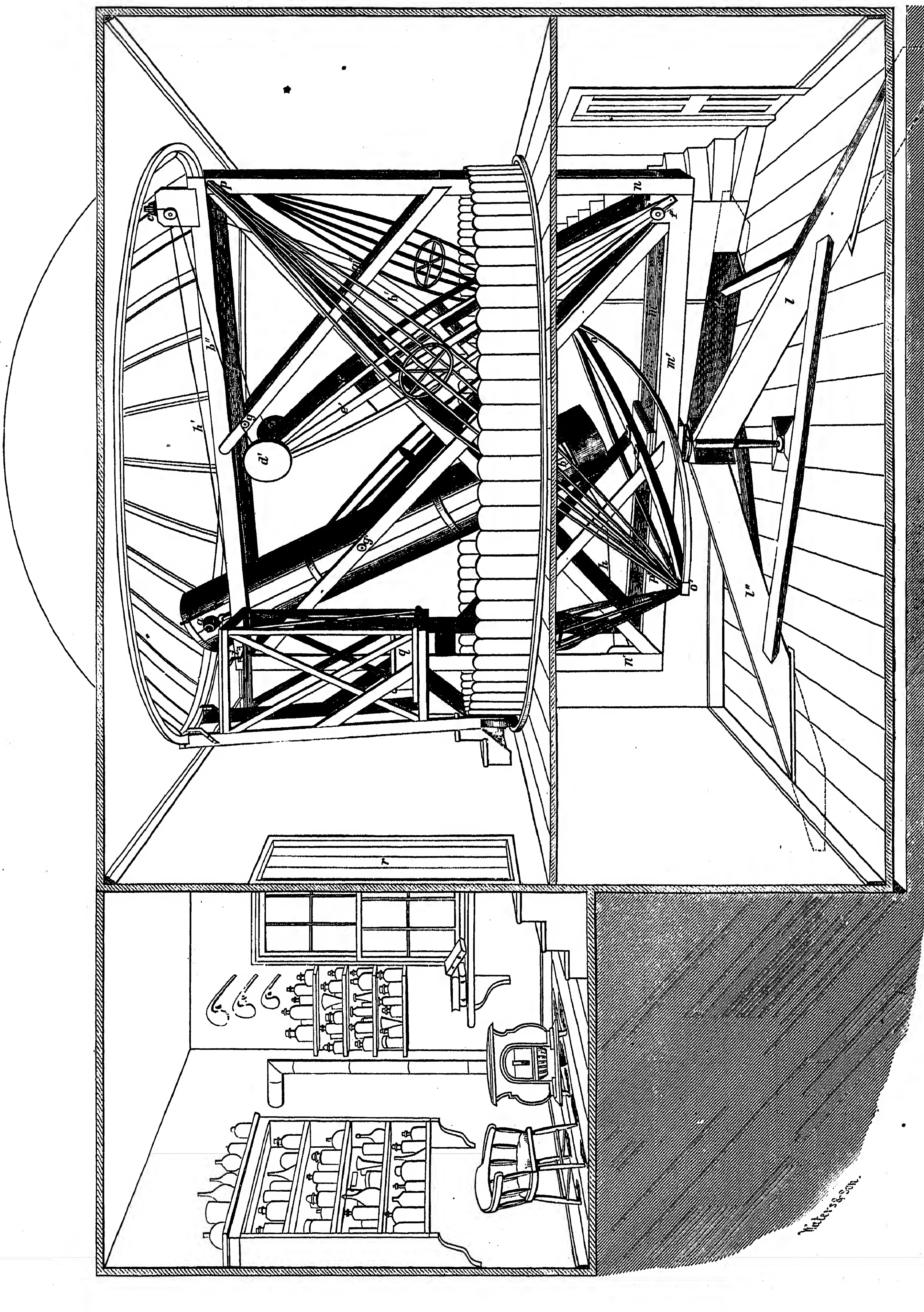
The obvious disadvantage connected with the alt-azimuth mounting—the difficulty of finding some objects—has not been a source of embarrasment. In fact the instability of the optical axis in reflecting instruments, if the mirror is unconstrainedly supported, as it should be, renders them unsuitable for determinations of position. A little patience will enable an observer to find all necessary tests, or curious objects.

The mounting is divided into: a. The Tube; and b. The supporting frame.

a. *The Tube.*

The telescope tube is a sixteen sided prism of walnut wood, 18 inches in diameter, and 12 feet long. The staves are $\frac{3}{8}$ of an inch thick, and are hooped together with four bands of brass, capable of being tightened by screws. Inside the tube are placed two rings of iron, half an inch thick, reducing the internal diameter to about 16 inches. At opposite sides of the upper end of the tube are screwed the perforated trunnions a, Fig. 28 (of which only one is shown), upon which it swings. Surrounding the other end is a wire rope $b\ b'\ b''$, the ends of which go over the pulleys c (c' not shown) on friction rollers, and terminate in disks of lead $d\ d'$. These counterpoises are fastened on the ends of levers $e\ e'$, which turn below on a fixed axle f.

By this arrangement as the tube assumes a horizontal position and becomes, so to speak, heavier, the counterpoises do the same, while when the tube becomes perpendicular, and most of its weight falls upon the trunnions, the counterpoises are carried mostly by their axle. A continual condition of equilibrium is thus reached, the tube being easily raised or depressed to any altitude desired. It is necessary, however, to constrain the wire rope $b\ b'\ b''$, to move in the arc of the circle described by the end of the tube and ends of the levers and hence the twelve rollers or guide pulleys $g\ g'\ g''$. Over some of the same pulleys a thin wire rope $h\ h'$ runs, but while its ends are fastened to the lower part of the tube at b, the central parts go twice around a roller connected with the winch i, near the eye-piece, thus enabling the observer to move the telescope in altitude, without taking the eye from the eye-piece.

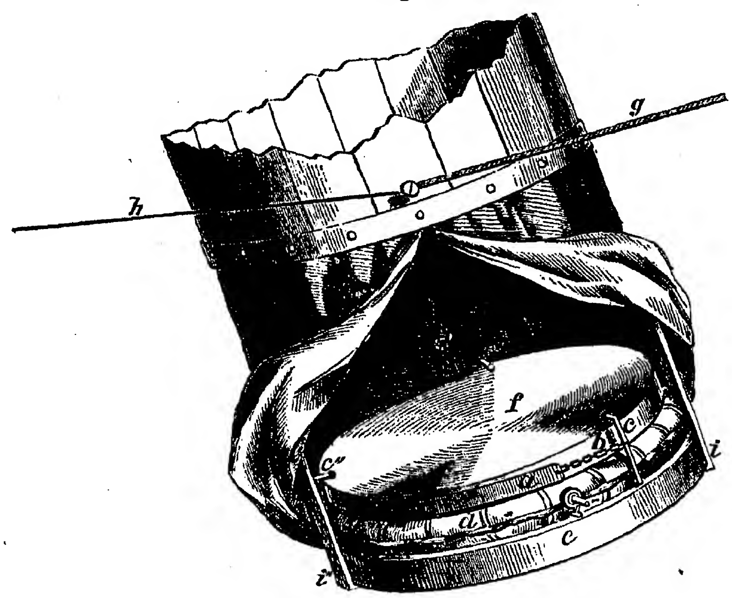


Sectional View of Observatory.

The iron wire rope required to be carefully made, so as to avoid rigidity. It contains $2\frac{1}{3}$ miles of wire, $\frac{1}{100}$ of an inch in diameter, and has 300 strands. Each single wire will support 7 pounds It is, however, more flexible than a hempen rope of the same size, owing to its loose twisting.

At the lower end of the tube, at the distance of a foot, and crossing it at right angles, held by three bars of iron $i\ i'\ i''$, Fig. 29, is a circular table of oak e, which

Fig. 29.



The Mirror Support.

carries an India-rubber air sac d, and upon this the mirror f is placed. The edge support of the mirror is furnished by a semicircular band of tin-plate a, lined inside with cotton, and fastened at the ends by links of chain b, (b' not seen) to two screws $c\ c'$; g and h are the wire ropes, marked b and h in Fig. 28.

Instead of the blanket support which Herschel found so advantageous, M. Foucault has suggested this use of an air sac. In his instrument there is a tube going up to the observer, by which he may adjust its degree of inflation. It requires that there should be three bearings $c\ c'\ c''$, in front of the mirror, against which it may press when the sac behind is inflated, otherwise the optical axis is altogether too instable, and objects cannot be found. The arrangement certainly gives beautiful definition, bringing stars to a disk when the glass just floats, without touching its front bearings. The first sac that I made was composed of two circular sheets of India-rubber cloth, joined around the edges. But this could not be used while photographing, because the image was kept in a state of continuous oscillation if there was a breeze, and even under more favorable circumstances took a long time to come to rest. It was not advisable to blow the mirror hard up against its three front bearings, in order to avoid the instability, for then every point in of an object became triple. To the eye the oscillations were not offensive, because the swaying image was sharp.

Subsequently, however, an air chair cushion was procured, and as the surface was flat instead of convex the difficulty became so much less, that the blanket support was definitely abandoned. It is necessary that the mirror should have free play in

the direction of the length of the tube when this kind of support is used, and that is the reason why the tin edge hoop must terminate in links of chain.

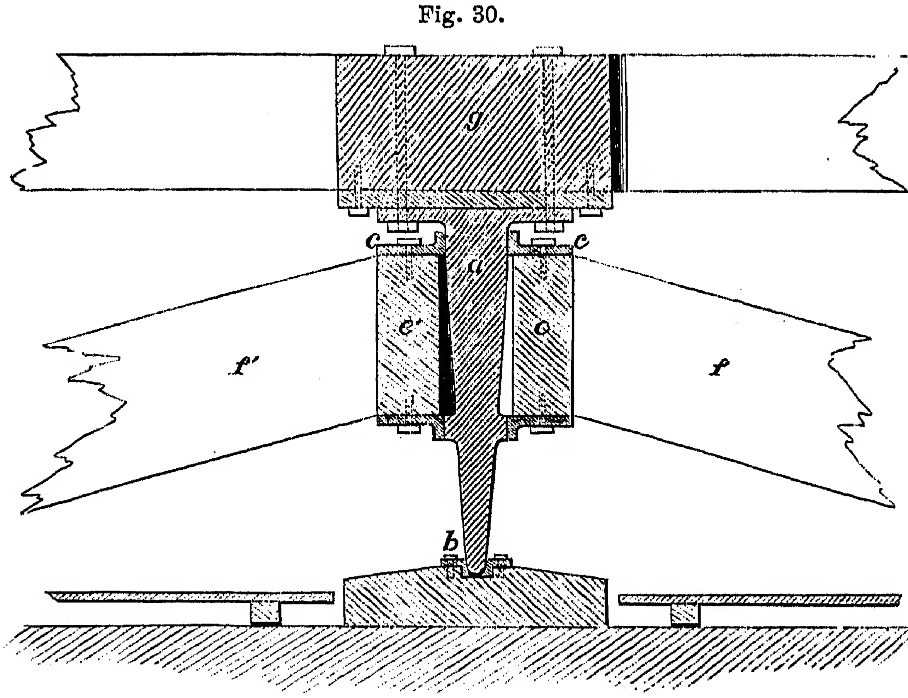
The interval, eight or ten inches, which separates the face of the mirror from the tube, is occupied by a curtain of black velvet, confined below by a drawing cord and tacked above to the tube. This permits access to the mirror to put a glass cover on it, and when shut down stops the current of air rushing up. When the instrument is not being used this curtain is left open, because the mirror and tube are in that case kept more uniform in temperature with the surrounding air.

In spite of such contrivances there is still sometimes a strong residual current in the tube. I have tried to overcome it by covering the mouth of the tube with a sheet of flat glass, but have been obliged to abandon that because the images were injured. At one time, too, when it was supposed that the current was partly from the observer's body, heated streams of air going out around the tube, the aperture in the dome was closed by a conical bag of muslin, which fitted the mouth of the telescope tightly. The only advantages resulting were mere bodily comfort and a capability of perceiving fainter objects than before, because the sky-light was shut off.

b. *The Supporting Frame.*

The frame which carries the preceding parts is of wood, and rests on a vertical axis *a*, Fig. 30, turning below in a gun-metal cup *b*, supported by a marble block

Fig. 30.

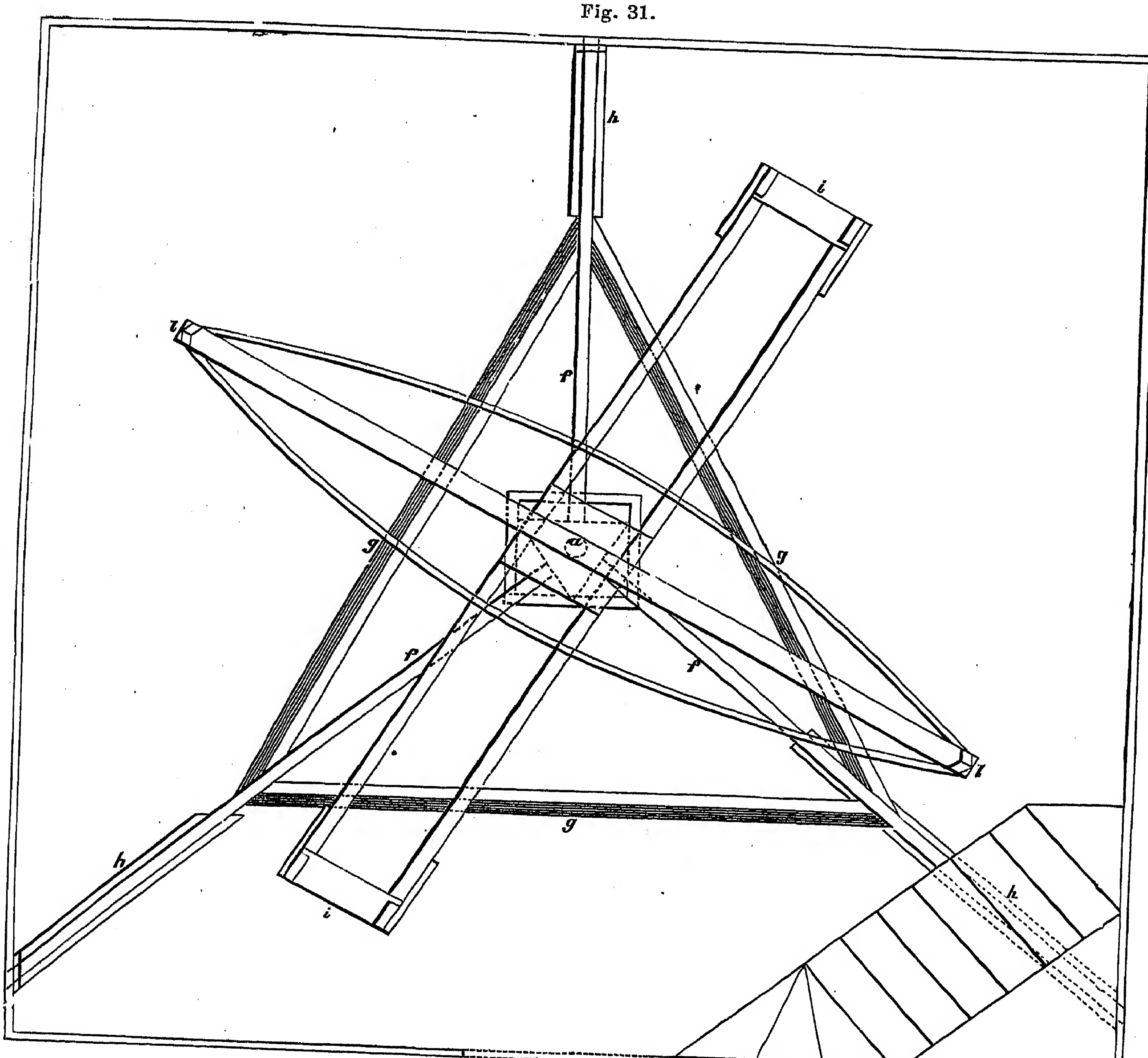


Section of Azimuth Axis.

resting on the solid rock. The upper end of the axis is sustained by two collars, one *c c'* above, and the other below an intermediate triangular box *e e'* from the sides of which three long beams *f f f* 12 × 3 inches diverge, gradually declining till they meet the solid rock at the limits of the excavation in which the observatory

is placed. These beams are fastened together by cross-pieces *g g g*, Fig. 31, and go through the floor in spaces *h h h*, so contrived that the floor does not touch them. At the ends they are cased with a thick leaden sheathing, to deaden vibration and prevent the access of moisture.

Fig. 31.



Plan of Observatory (lower floor).

This tripod support in connection with the sustaining of the telescope by the wire rope, gives that steadiness which is so essential in photography. Only a slight amount of force, about two pounds, is required to move the instrument in azimuth, though it weighs almost a thousand pounds.

The plan of the frame centrally carried by the axis *a* is as follows: From the corners of a parallelogram *i i* (2×13 feet) of wooden beams, eight inches thick and three inches broad, perpendiculars *n n′*, Fig. 28, rise. At the top they are connected by lighter pieces to form a parallelogram, similar to that below, and just

large enough to contain the tube of the telescope. At right angles to the parallelogram below, and close upon it, a braced bar *o o'*, Fig. 28, crosses. From its extremities four slanting braces as at *p p'*, Fig. 28, go to the corners of the upper parallelogram, and combine to give it lateral support. At the top of one close pair of the perpendiculars *n'*, Fig. 28, are bronze frames carrying friction rollers upon which the trunnions move, while similarly upon the other pair *n* are two pulleys, also on friction rollers, for the wire rope coming from the counterpoises.

Movement in altitude is very easily accomplished, and with the left hand upon the winch *i*, under high powers, both altitude and azimuth motions are controlled, and the right hand left free. The whole apparatus works so well, that in ordinary observation the want of a clock movement has not been felt. Of course for photography that is essential.

§ 3. THE CLOCK MOVEMENT.

The apparatus for following celestial bodies is divided into two parts; a. The Sliding Plate-holder; and b. The Clepsydra. In addition a short description of the Sun-Camera, c, is necessary.

a. *The Sliding Plate-holder.*

Mr. De La Rue, who has done so much for celestial photography, was the first to suggest photographing the moon on a sensitive plate, carried by a frame moving in the apparent direction of her path. He never, however, applied an automatic driving mechanism, but was eventually led to use a clock which caused the whole telescope to revolve upon a polar axis, and thus compensate for the rotation of the earth, and on certain occasions for the motion of the moon herself. In this way he has produced the best results that have been obtained in Europe. Lord Rosse, too, employed a similar sliding plate-holder, but provided with clock-work to move it at an appropriate rate. I have not been able as yet to procure any precise account of either of these instruments.

The first photographic representations of the moon ever made, were taken by my father, Professor John W. Draper, and a notice of them published in his quarto work "On the Forces that Organize Plants," and also in the September number, 1840, of the London, Edinburgh, and Dublin Philosophical Magazine. He presented the specimens to the New York Lyceum of Natural History. The Secretary of that Association has sent me the following extract from their minutes:—

"*March* 23*d*, 1840. Dr. Draper announced that he had succeeded in getting a representation of the moon's surface by the Daguerreotype . . . . . The time occupied was 20 minutes, and the size of the figure about 1 inch in diameter. Daguerre had attempted the same thing, but did not succeed. This is the first time that anything like a distinct representation of the moon's surface has been obtained.

"ROBT. H. BROWNNE, *Secretary.*"

As my father was at that time however much occupied with experiments on the Chemical Action of Light, the Influence of Light on the Decomposition of Car-

bonic Acid by Plants, the Fixed Lines of the Spectrum, Spectrum Analysis, &c., the results of which are to be found scattered through the Philosophical Magazine, Silliman's Journal, and the Journal of the Franklin Institute, he never pursued this very promising subject. Some of the pictures were taken with a three inch, and some with a five inch lens, driven by a heliostat.

In 1850, Mr. Bond, taking advantage of the refractor of 15 inches aperture at Cambridge, obtained some fine pictures of the moon, and subsequently of double stars, more particularly Mizar in Ursa Major. The driving power, in this instance, was also applied to move the telescope upon a polar axis.

Besides these, several English and continental observers, Messrs. Hartnup, Phillips, Crookes, Father Secchi, and others, have worked at this branch of astronomy, and, since 1857, Mr. Lewis M. Rutherfurd, of New York, has taken many exquisite lunar photographs, which compare favorably with foreign ones.

But in none of these instances has the use of the sliding plate-holder been persisted in, and its advantages brought into view. In the first place it gets rid completely of the difficulties arising from the moon's motion in declination, and in the second, instead of injuring the photograph by the tremors produced in moving the whole heavy mass of a telescope weighing a ton or more, it only necessitates the driving of an arrangement weighing scarcely an ounce.

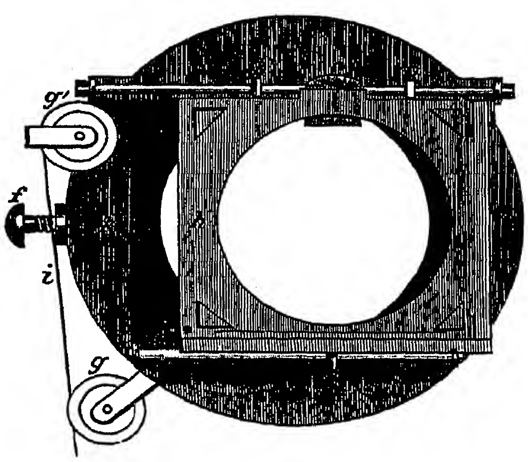
My first trials were with a frame to contain the sensitive plate, held only at three points. Two of these were at the ends of screws to be turned by the hands, and the third was on a spring so as to maintain firm contact. This apparatus worked well in many respects, but it was found that however much care might be taken, the hands always caused some tremor in the instrument. It was evident then that the difficulty from friction which besets the movements of all such delicate machinery, and causes jerking and starts, would have to be avoided in some other way.

I next constructed a metal slide to run between two parallel strips, and ground it into position with the greatest care. This, when set in the direction of the moon's apparent path, and moved by one screw, worked better than the preceding. But it was soon perceived that although the strips fitted the frame as tightly as practicable, an adhesion of the slide took place first to one strip and then to the other, and a sort of undulatory or vermicular progression resulted. The amount of deviation from a rectilinear motion, though small, was enough to injure the photographs. At this stage of the investigation the regiment of volunteers to which I belonged was called into active service, and I spent several months in Virginia.

My brother, Mr. Daniel Draper, to whose mechanical ingenuity I have on several occasions been indebted for assistance in the manifold difficulties that have arisen while constructing this telescope, continued these experiments at intervals. He presented me on my return with a slide and sand-clock, with which some excellent photographs have been taken.* He had found that unless the slide above mentioned was made ungovernably long, the same trouble continued. He then ceased catching the sliding frame *h*, Fig. 32, by two opposite sides, and made it run along a single steel rod *a*, being attached by means of two perforated plates of brass *b*, *b'*. The cord *i* going to the sand-clock, was applied so as to pull as nearly as possible in the direction of the rod. A piece of cork *c*, gave the whole steadiness, and yet

softness of motion. The lower end of the frame was prevented from swinging back and forward by a steel pin d, which played along the glass rod e. All these parts were attached to a frame k, fitting on the eyepiece holder, and permitting the rod a to change from the horizontal position in which it is here drawn, to any angular one desired. The thumb-screw f retained it in place; g and g' are pulleys which permit the cord to change direction.

Fig. 32.

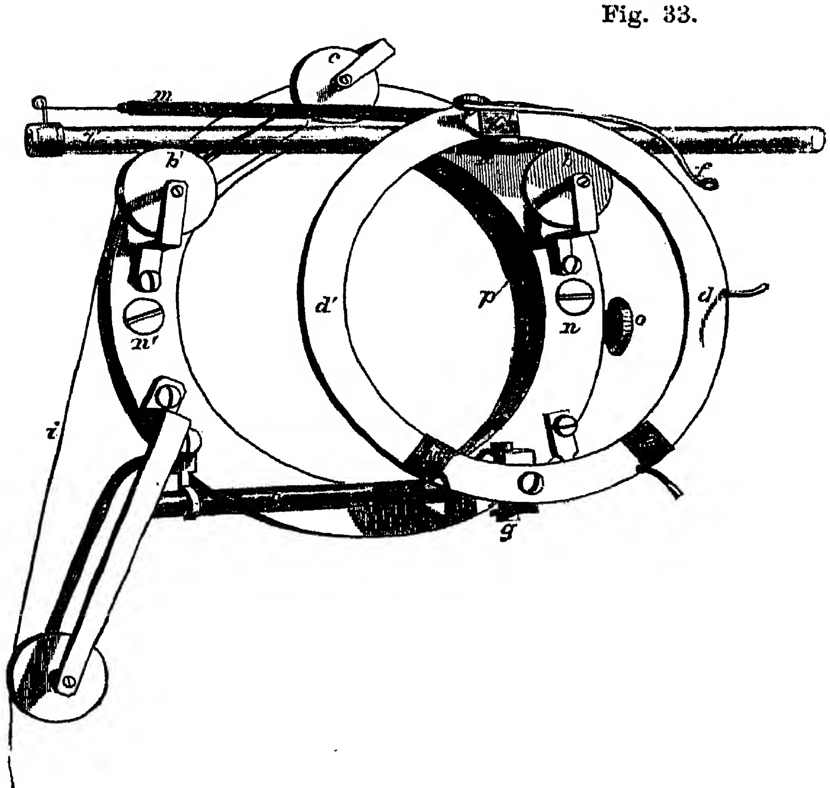


Sliding Plate-holder.

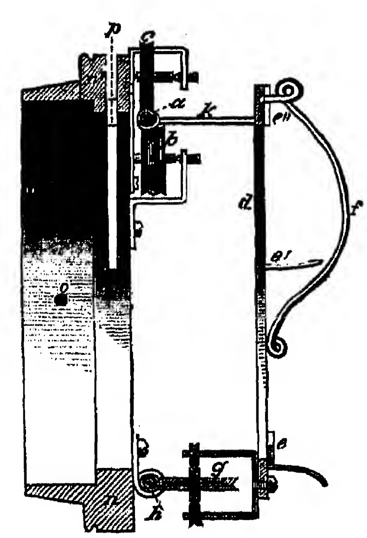
Subsequently, a better method of examining the uniformity of the rate, than by noticing the sharpness of the photograph produced, was invented. It consists in arranging a fixed microscope, magnifying about 40 times, at the back of the ground glass plate, which fits in the same slide as the sensitive plate. By watching the granulated appearance pass before the eye, as the slide is moved by the clock, the slightest variation from uniformity, any pulsatile or jerking movement is rendered visible. By the aid of this microscopic exaggeration, it was seen that occasionally, when there had been considerable changes in temperature, the steadiness of the motion varied. This was traced to the irregular slipping of b, b'.

A different arrangement was then adopted, by which a lunar crater can be kept bisected as long as is necessary, and which gives origin to no irregularities, but pursues a steady course. The principle is, not to allow a slipping friction anywhere, but to substitute rolling friction, upon wheels turning on points at the ends of their axles. The following wood-cut is half the real size of this arrangement.

Fig. 33.



Frictionless Slide (front view).



Sectional view.

A glass rod a, a', Fig. 33, is sustained by two wheels b, b', and kept in contact with them by a third friction roller c, pressed downward by a spring. This rod carries a circular frame d, d', upon which at e, e', e'', are three glass holders and platinum catches. A spring f holds the sensitive plate in position, by pressing against its back. The circular frame d is kept in one plane by a fourth friction roller g, which runs on a glass rod h, and is kept against it by the inward pressure of the overhanging frame d. The cord i is attached to the arm k, and pulls in the direction of the glass rod a. From m to a fixed point near b, a strip of elastic India-rubber is stretched, to keep the cord tight. The ring of brass n, n' carries the whole, serving as a basis for the stationary parts, and in its turn being fastened to the eyepiece holder, so as to allow the glass rod a to change direction, and be brought into coincidence with the apparent path of the moon. At o is a thumb-screw or clamp Through the ring n, n', a groove p is cut, into which a piece of yellow glass may be placed, when the actinic rays are to be shut off from the plate.

Since this contrivance has been completed, all the previous difficulties have vanished. The moving of a plate can be accomplished with such precision, that when the atmosphere was steady, negatives were taken which have been enlarged to three feet in diameter.

The length of time that such a slide can be made to run is indefinite, depending in my case on the size of the diagonal flat mirror, and aperture of the eyepiece holder. I can follow the moon for nearly four minutes, but have never required to do so for more than fifty seconds. At the mouth of the instrument, where no secondary mirror is necessary, the time of running could be increased.

The setting of the frictionless slide in angular position is accomplished as follows: A ground glass plate is put into it, with the ground face toward the mirror. Upon this face a black line must have been traced, precisely parallel to the rod a. This may be accomplished by firmly fixing a pencil point against the ground side, and then drawing the frame d and glass past it, while the rest of the slide is held fast. As the moon passes across the field, the position of the apparatus must be changed, until one of the craters runs along the line from end to end. A cross line drawn perpendicular to the other, serves to adjust the rate of the clepsydra as we shall see, and when a crater is kept steadily on the intersection for twice or three times the time demanded to secure an impression, the adjustment may be regarded as complete.

It is necessary of course to expose the sensitive plate soon after, or the apparent path of the moon will have changed direction, unless indeed the slide is set to suit a future moment.

b. *The Clepsydra.*

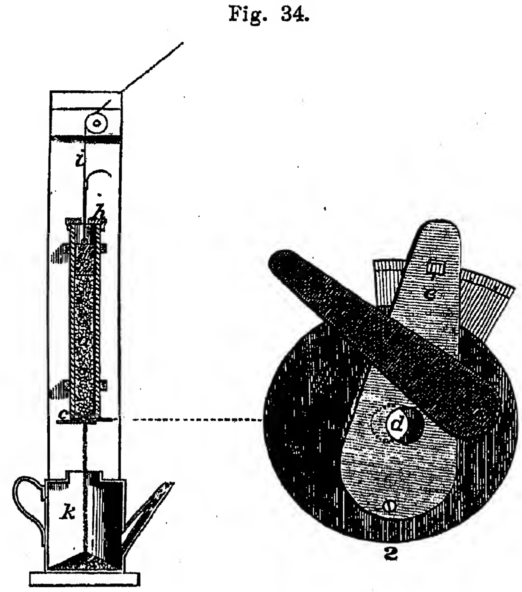
My prime mover was a weight supported by a column of sand, which, when the sand was allowed to run out through a variable orifice below, could be made to descend with any desired velocity and yet with uniformity. In addition, by these means an unlimited power could be brought to bear, depending on the size of the weight. Previously it was proposed to use water, and compensate for the decrease in flow, as the column shortened, by a conical vessel; but it was soon perceived that

as each drop of water escaped from the funnel-shaped vessel, only a corresponding weight would be brought into play. This is not the case with sand, for in this instance every grain that passes out causes the whole weight that is supported by the column to come into action. In the former instance a movement consisting of a series of periods of rest and periods of motion occurs, because power has to accumulate by floating weight lagging behind the descending water, and then suddenly overtaking it. In the latter case, on the contrary, there is a regular descent, all minor resistances in the slide being overcome by the steady application of the whole mass of the weight.

When these advantages in the flow of sand were ascertained, all the other prime movers were abandoned. Mercury-clocks, on the principle of the hydrostatic paradox, air-clocks, &c., in great variety, had been constructed.

The sand-clock consisted of a tube *a* (Fig. 34), eighteen inches long and one and a half in diameter, nearly filled with sand that had been raised to a bright red heat and sifted. Upon the top of the sand a leaden weight *b* was placed. At the bottom of the tube a peculiar stopcock, seen at (2) enlarged, regulated the flow, the amount passing depending on the size of the aperture *d*. This stopcock consisted of two thin plates, fixed at one end and free at the other. The one marked *e* is the adjusting lever, and its aperture moves past that in the plate *g*. The lever *f* serves to turn the sand off altogether, without disturbing the size of the other aperture, which, once set to the moon's rate, varies but slightly in short times. A movable cover *h*, perforated to allow the cord *i* to pass through, closed the top, while the vessel *k* retained the escaped sand, which at suitable times was returned into the tube *a*, the weight *b* being temporarily lifted out. From the clock the cord *i* communicated motion to the frictionless slide, as shown in Fig. 33. This cord should be as inelastic as possible, consistent with pliability, and well waxed.

Fig. 34.



The Sand-Clock.

One who has not investigated the matter would naturally suppose that the flow of sand in such a long tube would be much quicker when the tube was full than when nearly empty, and that certainly that result would occur when a heavy weight was put on the shifting mass. But in neither case have I been able to detect the slightest variation, for, although by shaking the tube a diminution of the space occupied by the sand may be caused, yet no increase of weight tried could accomplish the same reduction. These peculiarities seem to result from the sand arching as it were across the vessel, like shot in a narrow tube, and only yielding when the under supports are removed. In blasting, a heavy charge of gunpowder can be retained at the bottom of a hole, and made to split large masses of rock, by filling the rest of the hole with dry sand.

I believe that no prime mover is more suitable than a sand-clock for purposes where steady motion and a large amount of power are demanded. The simplicity, for instance, of a heliostat on this plan, the large size it might assume, and its small cost, would be great recommendations. In these respects its advantages over wheelwork are very apparent. The precision with which such a sand-clock goes may be appreciated when it is stated, that under a power of 300 a lunar crater can be kept bisected for many times the period required to photograph it. To secure the greatest accuracy in the rate of a sand-clock, some precautions must be taken. The tube should be free from dents, of uniform diameter, and very smooth or polished inside. Water must not be permitted to find access to the sand, and hygrometric varieties of that substance should be avoided, or their salts washed out. The sand should be burned to destroy organic matter, and so sifted as to retain grains nearly equal in size. The weight, which may be of lead, must be turned so as to go easily down the tube, and must be covered with writing paper or some other hard and smooth material, to avoid the proneness to adhesion of sand. A long bottle filled with mercury answers well as a substitute.

I have used in such clocks certain metallic preparations: Fine shot, on account of its equality of size, might do for a very large clock with a considerable opening below, but is unsuitable for a tube of the size stated above. There is, however, a method by which lead can be reduced to a divided condition, like fine gunpowder, when it may replace the sand. If that metal is melted with a little antimony, and while cooling is shaken in a box containing some plumbago, it breaks up at the instant of solidifying into a fine powder, which is about five times as heavy as sand. If after being sifted to select the grains of proper size, it is allowed to run through a small hole, the flow is seen to be entirely different from that of sand, looking as if a wire or solid rod were descending, and not an aggregation of particles. It is probable, therefore, that it would do better than sand for this purpose. I have not, however, given it a fair trial, because just at the time when the experiments with the sand-clock had reached this point, I determined to try a clepsydra as a prime mover.

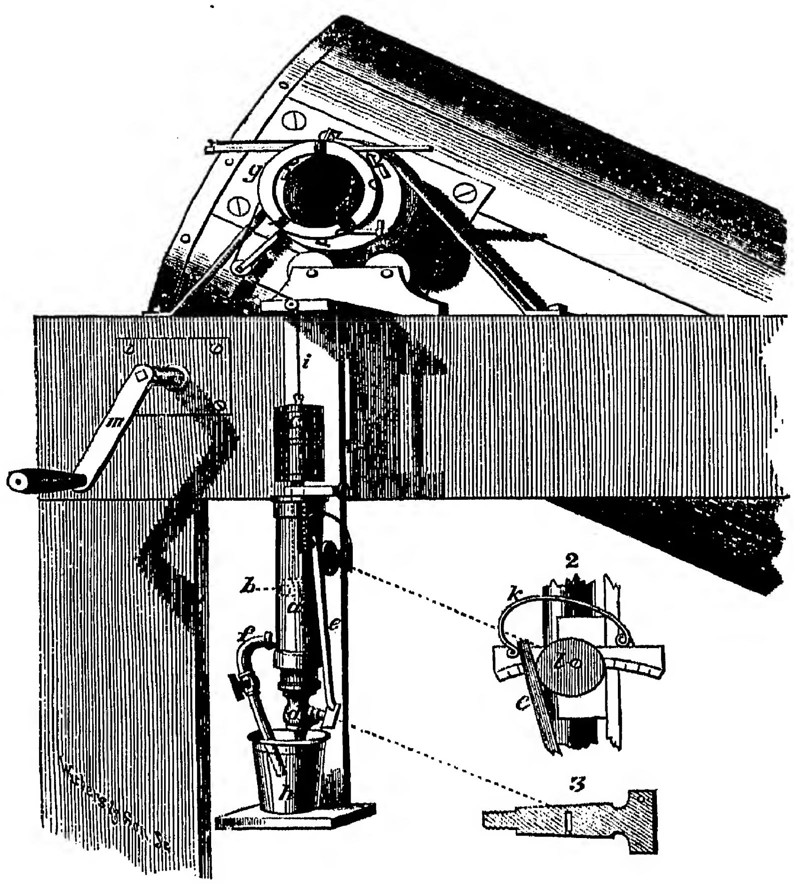
The reason which led to this change was that it was observed on a certain occasion when the atmosphere was steady, that the photographs did not correspond in sharpness, being in fact no better than on other nights when there was a considerable flickering motion in the air. A further investigation showed that in these columns of sand there is apt to be a minute vibrating movement. At the plate-holder above this is converted into a series of arrests and advances. On some occasions, however, these slight deviations from continuous motion are entirely absent, and generally, indeed, they cannot be seen, if the parts of the image seem to vibrate on account of currents in the air. By the aid of the microscopic exaggeration described on a former page—which was subsequently put in practice—they may be observed easily, if present.

When the negative produced at the focus of the great mirror is intended to be enlarged to two feet or more in size, these movements injure it sensibly. A variety of expedients was resorted to in order to avoid them, but none proved on all occasions successful.

It is obvious that in a water-clock, where the mobility of the fluid is so much

greater than that of solid grains, this difficulty would not arise. The following contrivance in which the fault of the ordinary clepsydra, in varying rate of flow as the column shortens, is avoided, was next made. With it the best results are attainable, and it seems to be practically perfect.

Fig. 35.



The Clepsydra.

It consists of a cylinder *a*, in which a piston *b* moves watertight. At the top of the piston rod is a leaden five-pound weight *c*, from which the cord *i* goes to the sliding plateholder *g*. The lower end of the cylinder terminates in a stopcock *d*, the handle of which carries a strong index rod *e*, moving on a divided arc. At *f* a tube with a stopcock is attached. Below, a vessel *h* receives the waste fluid.

In using the clepsydra the stopcock of *f* is opened, and the piston being pulled upwards, the cylinder fills with water from *h*. The stopcock is then closed, and if *d* also is shut, the weight will remain motionless. The string *i* is next connected with the slide, and the telescope turned on the moon. As soon as the slide is adjusted in angular position (page 36) the stopcock *d* is opened, until the weight *c* moves downwards, at a rate that matches the moon's apparent motion.

In order to facilitate the rating of the clepsydra, the index rod *e* is pressed by a spring *k* (2), against an excentric *l*. As the excentric is turned round, the stopcock *d* is of course opened, with great precision and delicacy. The plug of this stopcock (3) is not perforated by a round hole, but has a slit. This causes equal move-

ments in the rod *e*, to produce equal changes in the flow. The rating requires consequently only a few moments.

The object of the side tube *f* is to avoid disturbing *d* when it becomes necessary to refill the cylinder, for when it is once opened to the right degree, it hardly requires to be touched again during a night's work. In order to arrest the downward motion of the piston at any point, a clamp screws on the piston rod, and can be brought into contact with the cylinder head, as in the figure.

That this instrument should operate in the best manner, it is essential to have the interior of the brass cylinder polished from end to end, and of uniform diameter. If any irregularity should be perceived in the rate of going, it can be cured completely by taking out the piston, impregnating its leather stuffing with fine rotten stone and oil, and then rubbing it up and down for five minutes in the cylinder, so as to restore the polish. The piston and cylinder must of course be wiped, and regreased with a mixture of beeswax and olive oil (equal parts) after such an operation. In replacing the piston, the cylinder must be first filled with water, to avoid the presence of air, which would act as a spring.

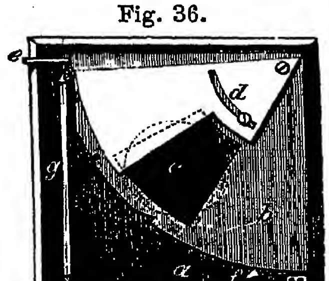
Although it may be objected that this contrivance seems to be very troublesome to use, yet that is not the case in practice. Even if it were, it so far surpasses any prime mover that I have seen, where the utmost accuracy is needed, that it would be well worth employing.

c. *The Sun Camera.*

In taking photographs of the sun with the full aperture of this telescope, no driving mechanism is necessary. On the contrary, the difficulty is rather to arrange the apparatus so that an exposure short enough may be given to the sensitive plate, and solarization of the picture avoided. It is not desirable to reduce the aperture, for then the separating power is lessened. The time required to obtain a negative is a very small fraction of a second, for the wavy appearance produced by atmospheric disturbance is not unfrequently observed sharply defined in the photograph, though these aerial motions are so rapid that they can scarcely be counted. Some kind of shutter that can admit and cut off the solar image with great quickness is therefore necessary.

In front of an ordinary camera *a*, Fig. 36, attached to the eyepiece holder of the telescope, and from which the lenses have been removed, a spring shutter is fixed.

Fig. 36.



The Spring Shutter.

It consists of a quadrant of thin wood *b*, fastened by its right angle to one corner of the camera. Over the hole in this quadrant a plate of tin *d* can be adjusted, and held in position by a screw moving in a slot so as to reduce the hole if desired to a mere slit. It may vary from $1\frac{1}{2}$ inch to less than $\frac{1}{50}$ of an inch. The quadrant is drawn downwards by an India-rubber spring *g*, 1 inch wide, $\frac{1}{8}$ of an inch thick, and 8 inches long. This spring is stretched when in action to about 12 inches, and when released draws the slit past the aperture *c* in the camera. Two nicks in the edge of the quadrant serve with the assistance of a pin *e*, which can easily be drawn out by a lever (not shown in the cut), to confine

the slit either opposite to or above *c*. A catch at *f* prevents the shutter recoiling. The sensitive plate is put inside the box as usual in a plate-holder. When a photograph is taken, the spring shutter is drawn up so that the lower nick in the edge of the quadrant is entered by the pin *e*, and the inside of the camera obscured. The front slide of the plateholder is then removed in the usual manner, and the solar image being brought into proper position by the aid of the telescope finder, the trigger retaining *e* is touched, the shutter flies past *c*, and the sensitive plate may then be removed to be developed.

To avoid the very short exposure needed when a silvered mirror of 188 square inches of surface is used, I have taken many solar photographs with an unsilvered mirror, which only reflects according to Bouguer $2\frac{1}{2}$ per cent. of the light falling upon it, and should permit an exposure 37 times as long as the silvered mirror. This is the first time that a plain glass mirror has been used for such a purpose, although Sir John Herschel suggested it for observation many years ago. But eventually this application of the unsilvered mirror had to be abandoned. It has, it is true, the advantage of reducing the light and heat, but I found that the moment the glass was exposed to the Sun, it commenced to change in figure, and alter in focal length. This latter difficulty, which sometimes amounts to half an inch, renders it well nigh impossible to find the focal plane, and retain it while taking out the ground glass, and putting in the sensitive plate. If the glass were supported by a ring around the edge, and the back left more freely exposed to the air, the difficulty would be lessened but not avoided, for a glass mirror can be raised to 120° F. on a hot day by putting it in the sunshine, though only resting on a few points. Other means of reducing the light and heat, depending on the same principle, can however be used. By replacing the silvered diagonal mirror with a black glass or plain unsilvered surface, as suggested by Nasmyth, the trouble sensibly disappears.

I have in this way secured not only maculæ and their penumbræ, but also have obtained faculæ almost invisible to observation. On some occasions, too, the precipitate-like or minute flocculent appearance on the Sun's disk was perceptible.

It seems, however, that the best means of acquiring fine results with solar photography, would be to use the telescope as a Cassegranian, and produce an image so much enlarged, that the exposure would not have to be conducted with such rapidity. Magnifying the image by an eyepiece would in a general way have the same result, but in that case the photographic advantages of the reflector would be lost, and it would be no better than an achromatic.

§ 4. THE OBSERVATORY.

This section is divided into *a*, The Building; *b*, The Dome; and *c*, The Observer's Chair.

a. *The Building.*

The Observatory is on the top of a hill, 225 feet above low water mark, and is in Latitude 40° 59′ 25″ north, and Longitude 73° 52′ 25″ west from Greenwich, according to the determinations of the Coast Survey. It is near the village of Hastings-upon-Hudson, and is about 20 miles north of the city of New York. The

surrounding country on the banks of the North River is occupied by country seats, on the slopes and summits of ridges of low hills, and no offensive manufactories

Fig. 37.

Dr. Draper's Observatory.

vitiate the atmosphere with smoke. Our grounds are sufficiently extensive to exclude the near passages of vehicles, and to avoid tremor and other annoyances.

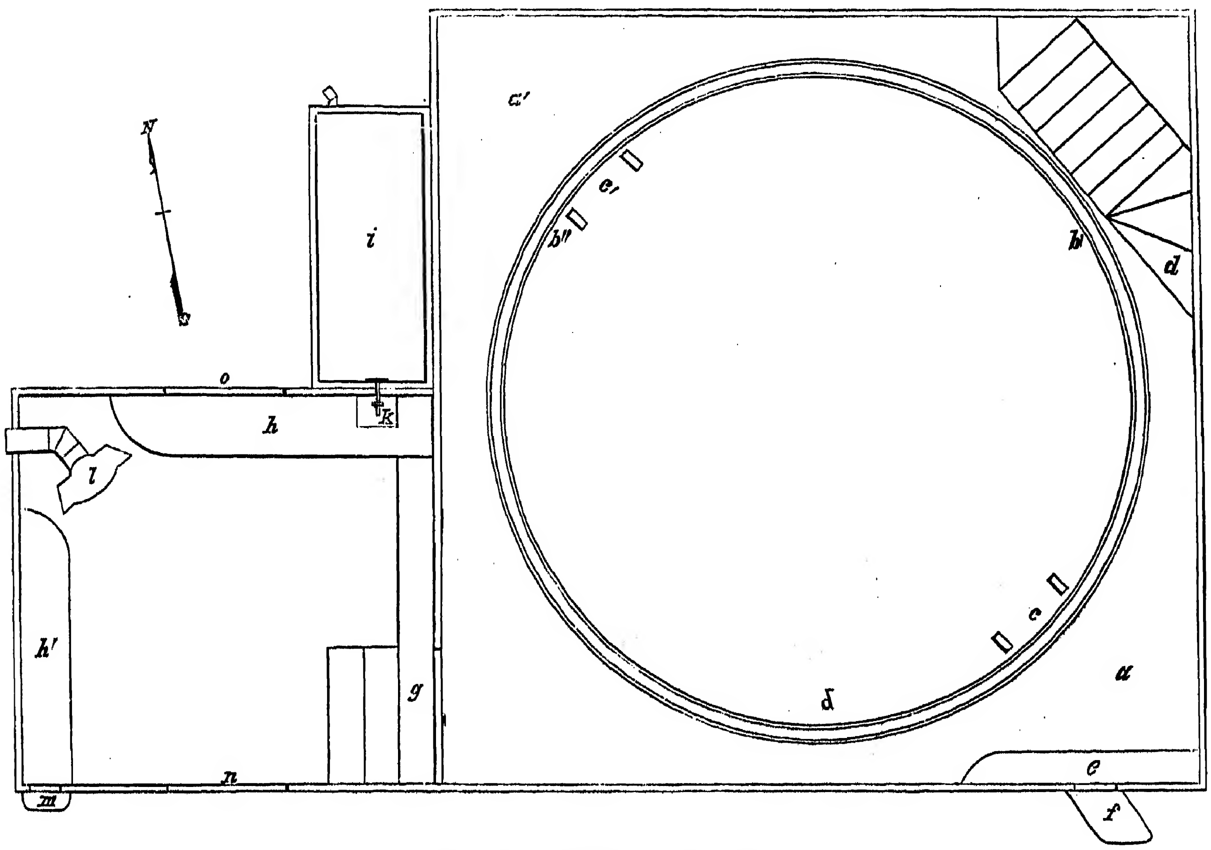
An uninterrupted horizon is commanded in every direction, except where trees near the dwelling house cut off a few degrees toward the southwest. The advantages of the location are very great, and often when the valleys round are filled with foggy exhalations, there is a clear sky over the Observatory, the mist flowing down like a great stream, and losing itself in the chasm through which the Hudson here passes.

The foundation and lower story of the building are excavated out of the solid granite, which appears at the edge of the hill. This arrangement was intended to keep the lower story cool, and avoid, in the case of the metal reflector, sudden changes of temperature. The eastern side of the lower story, however, projects over the brow of the hill, and is therefore freely exposed to the air, furnishing, when desired, both access and thorough ventilation through the door. The second story or superstructure is of wood, lined inside with boards like the story below. They serve to inclose in both cases a non-conducting sheet of air.

The inside dimensions of both stories taken together are $17\frac{1}{2}$ feet square, and 22 feet high, to the apex of the dome. This space is unnecessarily large for the tele-

scope, which only requires a cylinder 13 feet in diameter and 13 feet high. A general idea of the internal arrangement is gained from Fig. 28. In Fig. 38, *a a′* is the

Fig. 38.



Plan of Observatory (upper floor).

floor of the gallery, *b b′ b″* the circular aperture in which the telescope *c c′* turns. The staircase is indicated by *d*. The Enlarger, § 6, rests on the shelf *e*, the heliostat being outside at *f*. The door going into the photographic room is at *g*, *h h′* are tables, *i* the water tank, *k* the tap and sink, *l* the stove, *m* a heliostat shelf, *n* the door, *o* the window.

The building is kept ventilated by opening the door in the lower part, and the dome shutter, seen in Fig. 37, for some time before using the instrument. On a summer day the upper parts, and especially those close under the dome, become without this precaution very hot, and this occurred even before the tin roof was painted. Bright tinplate seems not to be able to reflect by any means all the heat that falls upon it, but will become so warm in July that rosin will melt on it, and insects which have lighted in a few moments dry up, and soon become pulverizable. A knowledge of these facts led to the abandonment of wooden sheathing under the tin, for without it when night comes on the accumulated heat radiates away rapidly, and ceases to cause aerial currents near the telescope.

The interior of the building is painted and wainscoted, and the roof is ornamented partly in blue and oak, and partly with panels of tulip-tree wood.

There are only two windows, and they are near the southern angles of the roof. While they admit sunshine on some occasions, they can on others be closed, and the interior be reduced to darkness. In the southeast corner a small opening *e*

may allow a solar beam three inches in diameter to come in from a heliostat outside. The greatest facilities are thus presented for optical and photographical experiments, for in the latter case the whole room can be used as a camera obscura.

b. *The Dome.*

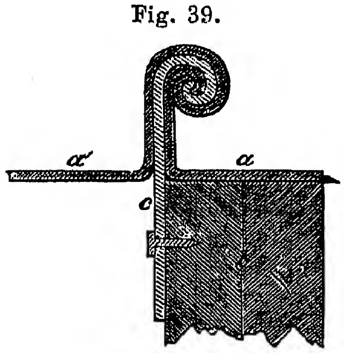
The roof of the observatory is 20 feet square. The angles are filled in solid, and a circular space 15 feet in diameter is left to be covered by the revolving dome. Although such a construction is architecturally weak and liable to lose its level, yet the great advantages of having the building below square, and the usefulness of the corners, determined its adoption, the disadvantages being overcome by a very light dome.

The dome is 16 feet in outside diameter, and rises to a height of 5 feet above its base. It is, therefore, much flatter than usual, in fact, might have been absolutely flat, with this method of mounting. It would then have been liable, however, to be crushed in by the deep winter snows.

It consists of 32 ribs, arcs of a circle, uniting at a common centre above. Each one is formed of two pieces of thin whitewood, *b*, Fig. 39, fastened side by side, with the best arrangements of the grain for strength. They are three inches wide and one inch thick at the lower end, and taper gradually to $2\frac{1}{2}$ by 1.

Over these ribs tinplate is laid in triangular strips or gores, about 18 inches wide at the base, and 10 feet long. Where the adjacent triangles of tin *a a′* meet, they are not soldered, but are bent together. This allows a certain amount of contraction and expansion, and is water-proof. It strengthens the roof so much, that if the ribs below were taken away, this corrugated though thin dome would probably sustain itself. The tin is fastened to the dome ribs *b* by extra pieces *c* inserted in the joint and doubled with the other parts, while below they are nailed to the ribs. In the figure the tin is represented very much thicker than it is in reality.

Fig. 39.



Joints in Tin of Dome.

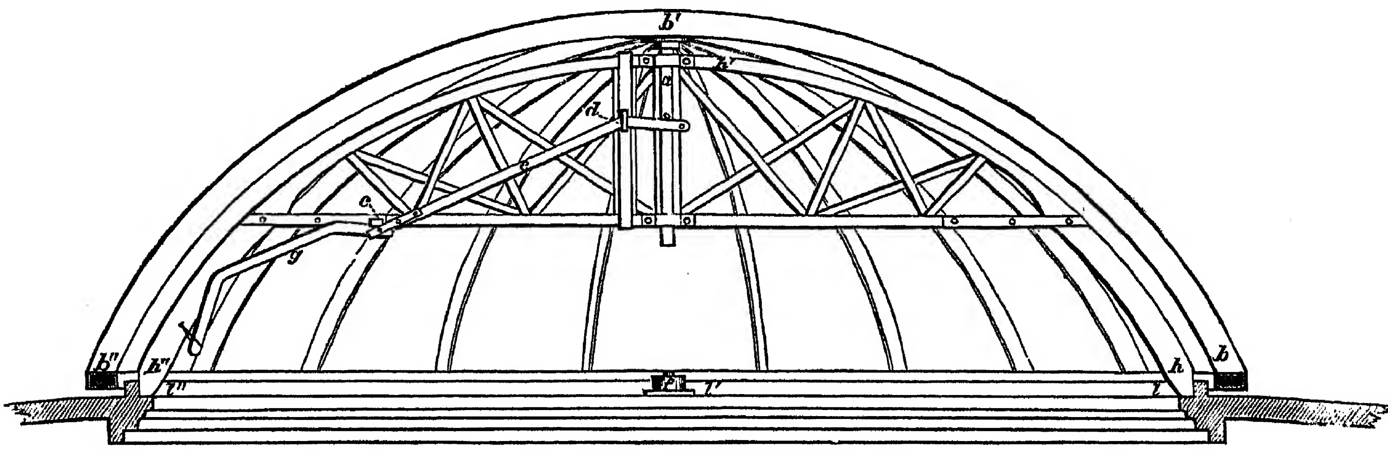
This dome, although it has 250 square feet of surface, only weighs 250 pounds. That at the Cambridge (Massachusetts) Observatory, $29\frac{1}{2}$ feet in diameter, weighs 28,000 pounds.

The slit or opening is much shorter than usual, only extending half way from the base towards the summit. It is in reality an inclined window, $2\frac{1}{2}$ feet wide at the bottom, $1\frac{1}{2}$ wide at the top, and 4 feet long. It is closed by a single shutter, as seen in Fig. 37, and this when opened is sustained in position by an iron rod furnished with a hinge at one end and a hook at the other.

The principal peculiarity of the dome, the means by which it is rotated, remains to be described. Usually in such structures rollers or cannon balls are placed at intervals under the edge, and by means of rack work, a motion of revolution is slowly accomplished. Here, on the contrary, the whole dome *b b′ b″* (Fig. 40) is supported on an arch *h h′ h″*, carrying an axis *a* at its centre, around which a slight direct force, a pull with a single finger, will cause movement, and by a sudden push even a quarter of an entire revolution may be accomplished. It is desirable, how-

ever, to let it rest on the edge $b\ b''$, when not in use. At c there is an iron catch on the arch, by which the lever e, that raises the dome, is held down. The fulcrum

Fig. 40.



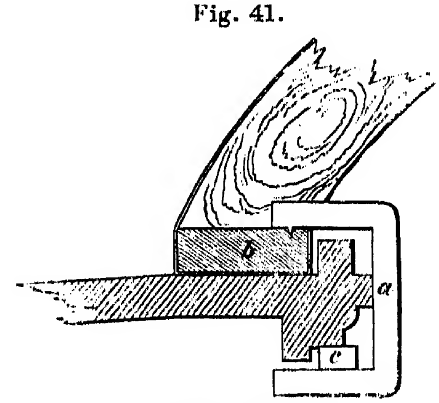
The Dome Arch.

is at d. The lever is hinged near c, so that when by being depressed it should have come in the way of the telescope below, the lower half g can be pushed up, the part from c toward d still holding the dome supported.

The arch can be set across the observatory in any direction, north and south, east and west, or at any intermediate position, because the abutments where the ends rest, are formed by a ring $l\ l'\ l''$, fastened round the circular aperture, through the stationary part of the roof.

When the telescope is not in use, and the dome is let down, so that there is no longer an interval of a quarter of an inch between it and the rest of the roof, it is confined inside by four clamps and wedges. Otherwise, owing to its lightness, it would be liable to be blown away. These clamps a, Fig. 41, are three sides of a square, made of iron one inch square. They catch above by a point in the wooden basis-circle of the dome b, and below are tightened by the wedge c.

Fig. 41.



A Dome Clamp.

When the dome is raised it is prevented from moving laterally and sliding off by three rollers, one of which is seen at f, Fig. 40. These catch against its inner edge, and only allow slight play. At first it was thought necessary to have a subsidiary half arch at right angles to the other to hold it up, but that is now removed.

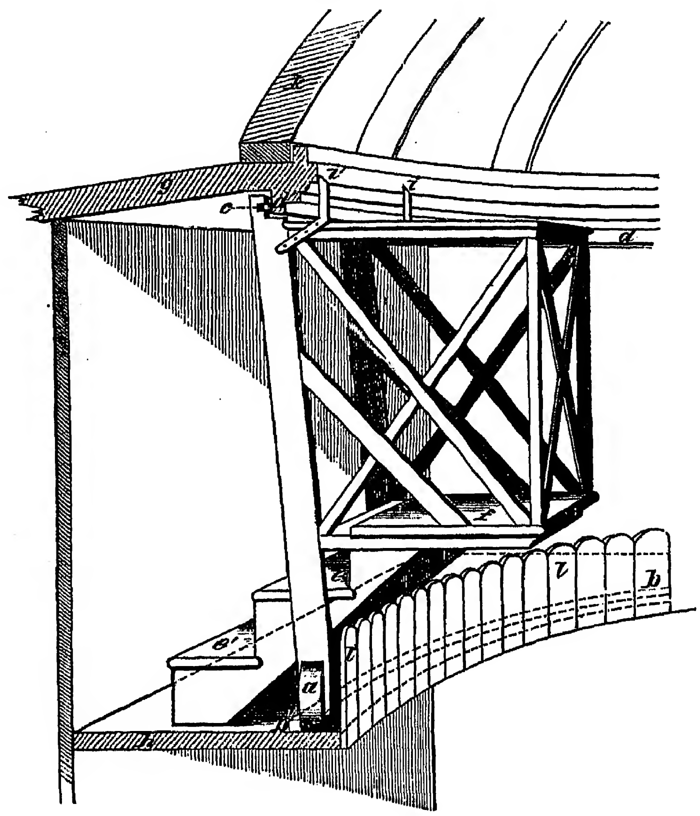
All the parts work very satisfactorily, and owing to the care taken to get the roof-circle and basis-circle flat and level, no leakage takes place at the joint, and even snow driven by high winds is unable to enter.

c. *The Observer's Chair.*

This is not a chair in the common acceptation of the word, but is rather a movable platform three feet square, capable of carrying two or more persons round the observatory, and maintaining them in an invariable position with regard to the telescope eyepiece.

Its general arrangement is better comprehended from the sketch, Fig. 42, than from a labored description. Below, it runs on a pair of wheels *a* (one only is

Fig. 42.



The Observer's Chair.

visible) 9 inches in diameter, whose axles point to the centre of the circle upon which they run. They are prevented from shifting outwards by a wooden railroad *b*, *b'*, and inwards by the paling *l*, *l'*. Above, the chair moves on a pair of small rollers *c*, which press against a circular strip or track *d*, *d'*, nailed around the lower edge of the dome opening. Access to the platform is gained by the steps *e*, *e'*. Attached to the railing of this platform, and near it on the telescope, are two tables (not shown in the figure) for eyepieces, the sliding plateholder, &c.

§ 5. THE PHOTOGRAPHIC LABORATORY.

This section is divided into *a*, Description of the Apartment; and *b*, Photographic Processes.

a. *Description of the Apartment.*

The room in which the photographical operations are carried on, adjoins and connects with the observatory on the southeast, as is shown in Figs. 28 and 38. It is 9 by 10 feet inside, and is supplied with shelves and tables running nearly all the way round, which have upon them the principal chemical reagents. It is furnished, too, with an opening to admit, from a heliostat outside, a solar beam of any size, up to three inches in diameter.

The supply of water is derived from rain falling on the roof of the building, and

running into a tank *i*, Fig. 38, which will contain a ton weight. The roof exposes a surface of 532 square feet, and consequently a fall of rain equal to one inch in depth, completely fills the tank. During the course of the year the fall at this place is about 32 inches, so that there is always an abundance. In order to keep the water free from contamination, the roof is painted with a ground mineral compound, which hardens to a stony consistence, and resists atmospheric influences well. The tank is lined with lead, but having been in use for many years for other purposes, is thoroughly coated inside with various salts of lead, sulphates, &c. In addition the precaution is taken of emptying the tank by a large stopcock when a rainstorm is approaching, so that any accumulation of organic matter, which can reduce nitrate of silver, may be avoided. It has not been found feasible to use the well or spring water of the vicinity.

The tank is placed close under the eaves of the building, so as to gain as much head of water as is desirable. From near its bottom a pipe terminating in a stopcock *k*, Fig. 38, passes into the Laboratory. In the northeast corner of the room, and under the tap is a sink for refuse water and solutions, and over which the negatives are developed. It is on an average about twelve feet distant from the telescope. In another corner of the room is a stove, resembling in construction an open fireplace, but sufficient nevertheless to raise the temperature to 80° F. or higher, if necessary. As a provision against heat in summer, the walls and roof are double, and a free space with numerous openings above is left for circulation of air, drawn from the foundations. The roof is of tinplate, fastened directly to the rafters, without sheathing, in order that heat may not accumulate to such an extent during the day as to constitute a source of disturbance when looking across it at night.

For containing negatives, which from being unvarnished require particular care, there is at one side of the room a case with twenty shallow drawers each to hold eighteen. They accumulate very rapidly, and were it not for frequent reselections the case would soon be filled. On some nights as many as seventeen negatives have been taken, most of which were worthy of preservation. Not less than 1500 were made in 1862 and '63.

b. *Photographic Processes.*

In photographic manipulations I have had the advantage of my father's long continued experience. He worked for many years with bromide and chloride of silver in his photo-chemical researches (Journal of the Franklin Institute, 1837), and when Daguerre's beautiful process was published, was the first to apply it to the taking of portraits (Phil. Mag., June, 1840) in 1839; the most important of all the applications of the art. Subsequently he made photographs of the interference spectrum, and ascertained the existence of great groups of lines *M*, *N*, *O*, *P*, above *H*, and totally invisible to the naked eye (Phil. Mag., May, 1843). The importance of these results, and of the study of the structure of flames containing various elementary bodies, that he made at the same time, are only now exciting the interest they deserve.

In 1850, when his work on Physiology was in preparation, and the numerous illustrations had to be produced, I learnt microscopic photography, and soon after

prepared the materials for the collodion process, then recently invented by Scott Archer. We produced in 1856 many photographs under a power of 700 diameters, by the means described in the next section.

At first the usual processes for portrait photography were applied to taking the Moon. But it was soon found necessary to abandon these and adopt others. When a collodion negative has to be enlarged—and this is always the case in lunar photography, where the original picture is taken at the focus of an object glass or mirror—imperfections invisible to the naked eye assume an importance which causes the rejection of many otherwise excellent pictures. Some of these imperfections are pinholes, coarseness of granulation in the reduced silver, liability to stains and markings, spots produced by dust.

These were all avoided by washing off the free nitrate of silver from the sensitive plate, before exposing it to the light, and again submitting it to the action of water, and dipping it back into the nitrate of silver bath before developing. The quantity of nitrate of silver necessary to development when pyrogallic acid is used, is however better procured by mixing a small quantity of a standard solution of that salt with the acid.

The operation of taking a lunar negative is as follows. The glass plates $2\frac{3}{4} \times 3\frac{1}{4}$ inches are kept in nitric acid and water until wanted. They are then washed under a tap, being well rubbed with the fingers, which have of course been properly cleaned. They are wiped with a towel kept for the purpose. Next a few drops of iodized collodion are poured on each side, and spread with a piece of cotton flannel. They are then polished with a large piece of this flannel, and deposited in a close dry plate box. This system of cleaning with collodion was suggested by Major Russel, to whose skilful experiments photography is indebted for the tannin process. It certainly is most effective, the drying pyroxyline removing every injurious impurity. There is never any trouble from dirty plates.

The stock of plates for the night's work, a dozen or so, being thus prepared, one of them is taken, and by movement through the air is freed from fibres of cotton. It is then coated with filtered collodion being held near the damp sink. The coated plate, when sufficiently dry, is immersed in a 40 grain nitrate of silver bath, acidified with nitric acid until it reddens litmus paper. The exact amount of acid in the bath makes in this "Washed Plate Process" but little difference. When the iodide and bromide of silver are thoroughly formed the plate is removed, drained for a moment, and then held under the tap till all greasiness, as it is called, disappears. Both front and back receive the current in turn.

It is then exposed, being carried on a little wooden stand, Fig. 43, covered with filtering paper to the telescope, and deposited on the sliding plateholder which has been set to the direction and rate of the moon, while the plate was in the bath. The time of exposure is ascertained by counting the beats of a half-second pendulum.

The method by which exposure without causing tremor is accomplished, is as follows: A yellow glass slides through the eyepiece-holder, Fig. 33, just in front of the sensitive plate, and is put in before the plate. The yellow-colored moon is centred on the collodion film, and the clepsydra and slide are set in motion, the

mass of the telescope being at rest. A pasteboard screen is put in front of the telescope, and the yellow glass taken out. After 20 seconds the instrument remaining still untouched and motionless, the screen is withdrawn, and as many seconds allowed to elapse as desirable. The screen is then replaced and the plate taken back to the photographic room.

Fig. 43.

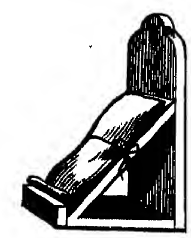


Plate Carrier.

After being again put under the tap to remove any dust or impurity, it is dipped into the nitrate bath for a few seconds. Two drachms of a solution of protosulphate of iron 20 grains, acetic acid 1 drachm, and water 1 ounce, is poured on it. As soon as the image is fairly visible this is washed off, and the development continued if necessary with a weak solution of pyrogallic acid and citro-nitrate of silver—pyrogallic and citric acids each $\frac{1}{5}$ grain, nitrate of silver $\frac{1}{10}$ grain, water 1 drachm. In order to measure these small quantities standard solutions of the substances are made, so that two drops of each contain the desired amount. They are kept in bottles, through the corks of which pipettes descend to just below the level of the liquid. This avoids all necessity of filtering, and yet no blemishes are produced by particles of floating matter.

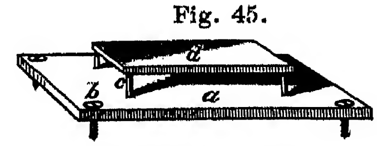
Fig. 44.

Pipette Bottle.

During the earlier part of the development, when the protosulphate of iron is on the film, an accurate judgment can be formed as to the proper length of time for the exposure in the telescope. If the image appears in 10 seconds, it will acquire an appropriate density for enlargement in 45 seconds, and will have the minimum of what is called fogging and the smallest granulations. If it takes longer to make its first appearance the exposure must be lengthened, and vice versa.

The latter part of the development, when re-development is practised, is purposely made slow, so that the gradation of tones may be varied by changing the proportion of the ingredients. As it would be tiresome and uncleanly to hold the plates in the hand, a simple stand is used to keep them level. It consists of a piece of thin wood *a*, Fig. 45, with an ordinary wood screw, as at *b*, going through each corner. Four wooden pegs, as at *c*, furnish a support for the plate *d*. By the aid of this contrivance and the washing system, I seldom get my fingers marked, and what is much more important, rarely stain a picture.

Fig. 45.



Developing Stand.

When the degree of intensity most suitable for subsequent enlargement is reached, that is, when the picture is like an overdone positive, the plate is again flooded with water, treated with cyanide of potassium or hyposulphite of soda, once more washed and set upon an angle on filtering paper to dry. It is next morning labelled, and put away unvarnished in the case.

To the remark that this process implies a great deal of extra trouble, it can only be replied that more negatives can be taken on each night than can be kept, and that, even were it not so, one good picture is worth more than any number of bad ones.

Although the above is the method at present adopted, and by which excellent results have been obtained, it may at any moment give place to some other, and is indeed being continually modified. The defects it presents are two—first, the time

of exposure is too long, and second, there is a certain amount of lateral diffusion in the thickness of the film, and in consequence a degree of sharpness inferior to that of the image produced by the parabolic mirror. The shortest time in which the moon has been taken in this observatory has been one-third of a second, on the twenty-first day, but on that occasion the sky was singularly clear, and the intrinsic splendor of the light great. The full moon under the same circumstances would have required a much shorter exposure. A person, however, who has put his eye at the focus of such a silvered mirror will not be surprised at the shortness of the time needed for impressing the bromo-iodide film; the brilliancy is so great that it impairs vision, and for a long time the exposed eye fails to distinguish any moderately illuminated object. The light from 188 square inches of an almost total reflecting surface is condensed upon 2 square inches of sensitive plate.

Occasionally a condition of the sky, the reverse of that mentioned above, occurs. The moon assumes a pale yellow color, and will continue to be of that non-actinic tint for a month or six weeks. This phenomenon is not confined to special localities, but may extend over great tracts of country. In August, 1862, when our regiment was encamped in Virginia, at Harper's Ferry, the atmosphere was in this condition there, and was also similarly affected at the observatory, more than 200 miles distant. As to the cause, it was not forest or prairie fires, for none of them of sufficient magnitude and duration occurred, but was probably dust in a state of minute division. No continued rain fell for several weeks, and the clay of the Virginia roads was turned into a fine powder for a depth of many inches. The Upper Potomac river was so low that it could be crossed dry-shod. On a subsequent occasion when the same state of things occurred again, I exposed a series of plates (whose sensitiveness was not less than usual, as was proved by a standard artificial flame) to the image of the full moon in the $15\frac{1}{2}$ inch reflector for 20 seconds, and yet obtained only a moderately intense picture. This was 40 times as long as common.

Upon all photographic pictures of celestial objects the influence of the atmosphere is seen, being sometimes greater and sometimes less. To obtain the best impressions, just as steady a night is necessary as for critical observations. If the image of Jupiter is allowed to pass across a sensitive plate, a streak almost as wide as the planet is left. It is easily seen not to be continuous, as it would have been were there no atmospheric disturbances, but composed of a set of partially isolated images. Besides this planet, I have also taken impressions of Venus, Mars, double stars, &c.

An attempt has been made to overcome lateral diffusion in the thickness of the film by the use of dry collodion plates, more particularly those of Major Russel and Dr. Hill Norris. These present, it is true, a fine and very thin film during exposure, but while developing are so changed by wetting in their mechanical condition that no advantage has resulted. It was while trying them, that I ascertained the great control that hot water exercises over the rapidity of development, and time of exposure, owing partly no doubt to increase of permeability in the collodion film, but also partly to the fact that chemical decompositions go on more rapidly at higher temperatures. I have attempted in vain to develop a tannin plate when it and the solutions used were at 32° F., and this though it had had a hundred times the exposure to light that was demanded when the plate was kept at 140° F. by warm water.

Protochloride of palladium, which I introduced in 1859, is frequently employed when it is desired to increase the intensity of a negative without altering its thickness. This substance will augment the opacity 16 times, without any tendency to injure the image or produce markings. It is only at present kept out of general use by the scarcity of the metal.

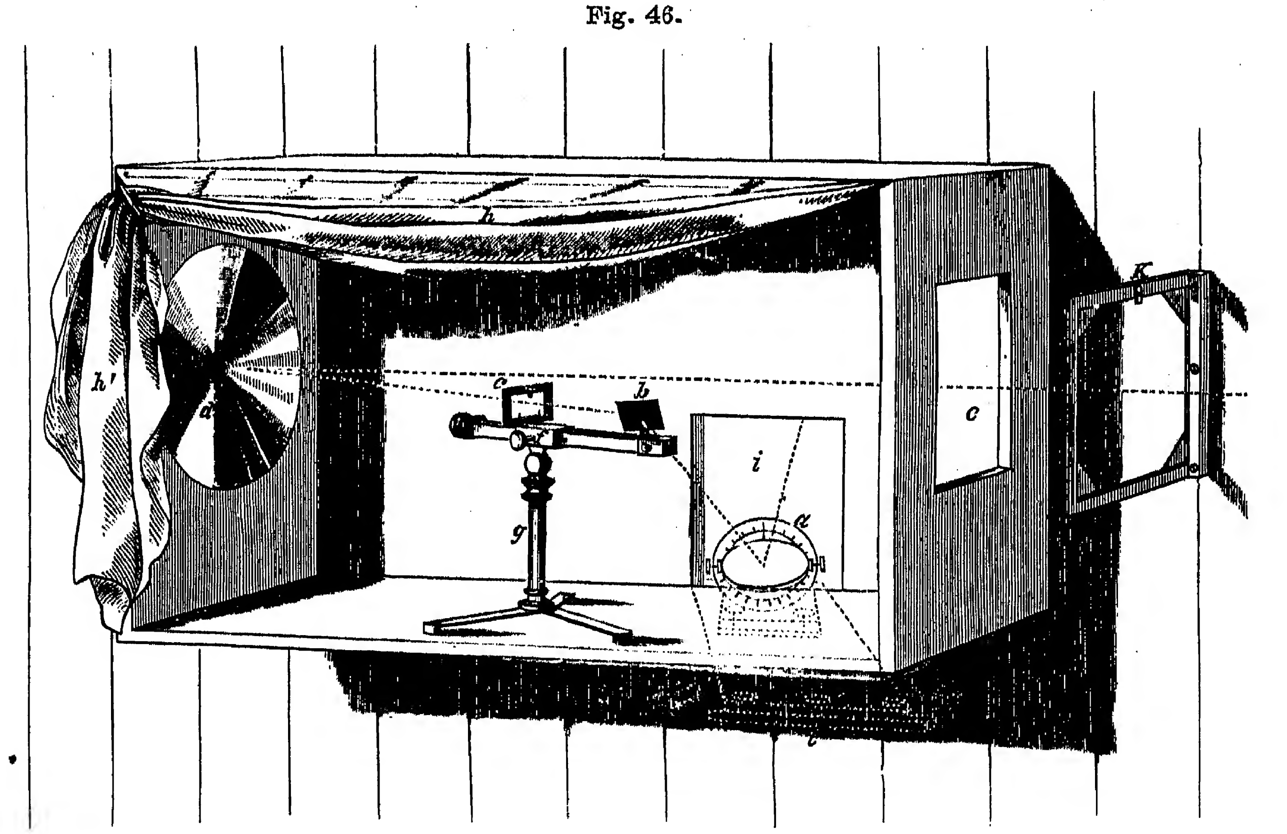
§ 6. THE PHOTOGRAPHIC ENLARGER.

Two distinct arrangements are used for enlarging, *a*, for Low Powers varying from 1 to 25; and *b*, for High Powers from 50 to 700 diameters.

a. *Low Powers.*

The essential feature in this contrivance is an entire novelty in photographic enlargement, and it is so superior to solar cameras, as they are called, that they are never used in the observatory now. It consists in employing instead of an achromatic combination of lenses, a *mirror* of appropriate curvature to magnify the original negatives or objects. The advantages are easily enumerated, perfect coincidence of visual and chemical foci, flat field, absolute sharpness of definition. If the negative is a fine one, the enlarged proofs will be as good as possible.

Fig. 46.



The Photographic Enlarger.

The mirror is of 9 inches aperture, and $11\frac{1}{2}$ inches focal length. It was polished on my machine to an elliptical figure of 8 feet distance between the conjugate foci, and was intended to magnify 7 times. At first the whole mirror was allowed to officiate, the object being illuminated by diffused daylight. But it was soon ap-

parent, that although a minute object placed in one focus was perfectly reproduced at the other, seven times as large, yet a large one was not equally well defined in all its parts.

I determined then to produce the enlarged image by passing a solar-beam $1\frac{1}{2}$ inch in diameter through the original lunar negative—placed in the focus nearest to the mirror—and allowing it to fall on a portion of the concave mirror, $1\frac{1}{2}$ inch in diameter, at one side of the vertex. Being reflected, it returns past the negative, and goes to form the magnified image at the other focus of the ellipse.

In Fig. 46, *a* is the heliostat on a stone shelf outside; *b* a silvered glass mirror, to direct the parallel rays through *c*, the negative; *d* is the elliptical mirror; *e* an aperture to be partly closed by diaphragms; *f* a rackwork movement carried by the tripod *g*; the curtain *h h'* shuts out stray light from the interior of the observatory. The aperture *i* is also diaphragmed, but is shown open to indicate the position of the heliostat, the shelf of which joins the outside of the building at *l*. The dotted line points out the course of the light, which coming from the sun falls on the heliostat mirror *a*, then on *b*, through *c* to *d*, and thence returning through *e* to the sensitive plate in the plate holder *k*.

The distance of this last can be made to vary, being either two feet or twenty-eight feet from *d*. In the latter case a magnifying power of about 25 results, the moon being made three feet in diameter. The sensitive plate is carried by a frame, which screws to the side wall of the building, and can be easily changed in position. The focussing is accomplished by the rack *f*. Where so small a part ($1\frac{1}{2}$ inch) of the surface of the mirror is used, a rigid adherence then to the true foci of this ellipse is not demanded, the mirror seeming to perform equally well whether magnifying 7 or 25 times. Theoretically it would seem to be limited to the former power.

If instead of placing a lunar photograph, which in the nature of the case is never absolutely sharp, at *c*, some natural object, as for instance a section of bone, is attached to the frame moved by *f*, then under a power of 25 times it is as well defined as in any microscope, while at the same time the amount of its surface seen at once is much larger than in such instruments, and the field is flat. If the intention were, however, to make microscopic photographs, a mirror of much shorter focal length would be desirable, one approaching more to those of Amici's microscopes.

By the aid of a concave mirror used thus obliquely, or excentrically, all the difficulties in the way of enlarging disappear, and pictures of the greatest size can be produced in perfection. I should long ago have made lunar photographs of more than 3 feet in diameter, except for the difficulties of manipulating such large surfaces.

In order to secure a constant beam of sunlight a heliostat is placed outside the observatory, at its southeast corner *f*, Fig. 38. This beam, which can be sent for an entire day in the direction of the earth's axis, is intercepted as shown at *b*, Fig. 46, and thus if needed an exposure of many hours could be given. The interior of the observatory and photographic room being only illuminated by faint yellow rays, no camera box is required to cut off stray light. The eye is by these means kept in a most sensitive condition, and the focussing can be effected with the critical

accuracy that the optical arrangement allows, no correction for chromatic aberration being demanded.

I have made all the parts of this apparatus so that they can be easily separated or changed. The flat mirrors are of silvered glass, and are used with the silvered side toward the light, to avoid the double image produced when reflection from both sides of a parallel plate of glass is permitted. The large concave mirror happens to be of speculum metal, but it can be repolished if necessary by means of a four inch polisher, passed in succession over every chord of the face. A yellow film of tarnish easily accumulates on metal specula if they are not carefully kept, and decreases their photographic power seriously.

Of the making of Reverses.— In addition to the use of the Enlarger for magnifying, it is found to have important advantages in copying by contact. The picture of the image of the moon produced in the telescope is negative, that is, the lights and shades are reversed. In enlarging such a negative reversal again takes place, and a positive results. This positive cannot, however, be used to make prints on paper, because in that operation reversing of light and shade once more occurs. It is necessary then at some stage to introduce still another reversal. This may be accomplished either by printing from the original negative a positive, which may be enlarged, or else printing from the enlarged positive a negative to make the paper proofs from. In either case a collodion film, properly sensitized, is placed behind the positive or negative, and the two exposed to light.

If diffused light or lamplight is used, the two plates must be as closely in contact as possible, or the sharpness of the resulting proof is greatly less than the original. This is because the light finds its way through in many various directions. If the two plates, however, are placed in the cone of sunlight coming from the Enlarger, and at a distance of fifteen or twenty feet from it, the light passes in straight lines and only in one direction through the front picture to the sensitive plate behind. I have not been able to see under these circumstances any perceptible diminution in sharpness, though the plates had been $\frac{1}{16}$ of an inch apart. It is perfectly feasible to use wet collodion instead of dry plates, no risk of scratching by contact is incurred, and the whole operation is easily and quickly performed. The time of exposure, 5 seconds, is of convenient length, but may be increased by putting a less reflecting surface or an unsilvered glass mirror in the heliostat. A diaphragm with an aperture of half an inch if placed at *e*, Fig. 46, to shut out needless light, and avoid injuring the sharpness of the reverse by diffusion through the room. In enlarging other diaphragms are also for the same reason put in the place of this one. For a half moon for instance, a yellow paper with a half circular aperture, whose size may be found by trial in a few minutes, is pinned against *e*.

The enlarged pictures obtained by this apparatus are much better than can be obtained by any other method known at present. The effect, for instance, of a portrait, made life-size, is very striking. Some astronomers have supposed that advantages would arise from taking original lunar negatives of larger size in the telescope, that is, from enlarging the image two or three times by a suitable eyepiece or concave achromatic, before it reached the sensitive plate. But apart from the fact that a reflector would then have all the disadvantages of an achromatic,

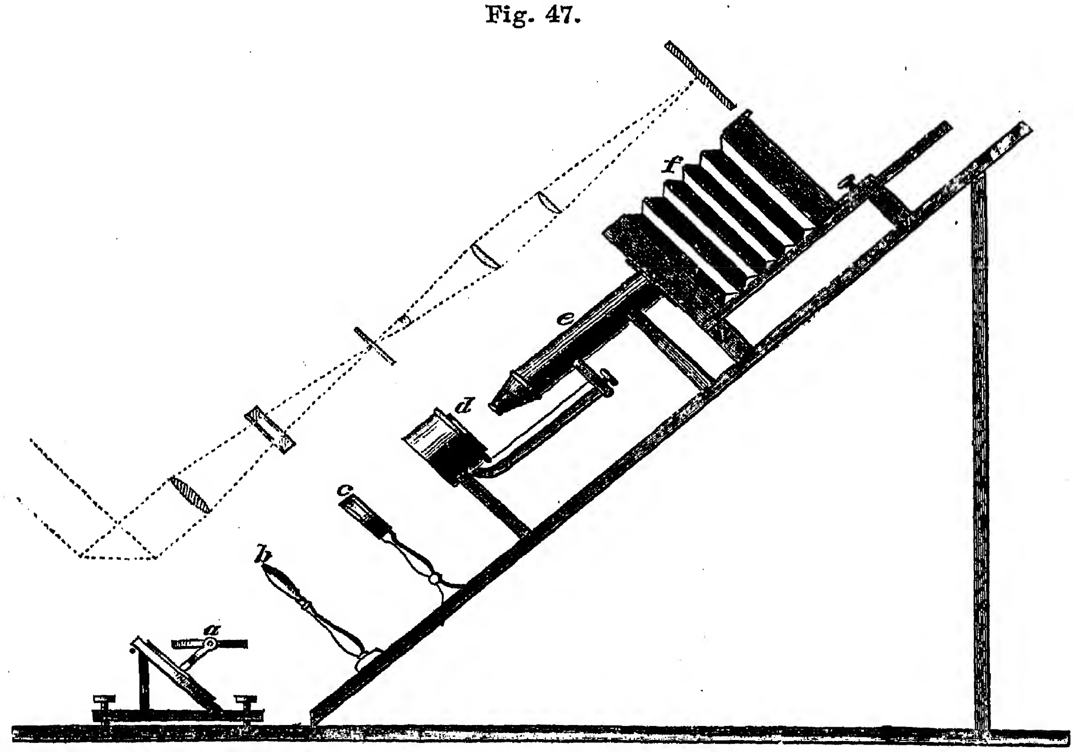
the atmospheric difficulties, which in reality constitute the great obstacle to success, would not be diminished by such means. The apparent advantage, that of not magnifying defects in the collodion, is not of much moment, for when development of the photographs is properly conducted, and thorough cleanliness practised, imperfections are not produced, and the size of the silver granules is not objectionable.

b. *High Powers.*

Although negatives of astronomical objects have not as yet been made which could stand the high powers of the arrangement about to be described, yet they bear the lower powers well, and give promise of improvement in the future.

Photography of microscopic objects as usually described, consists in passing a beam of light through the transparent object into the compound body of the microscope, and receiving it on its exit from the eyepiece upon a ground glass or sensitive plate. The difficulty which besets the instrument generally, and interferes with the production of fine results, arises from the uncertainty of ascertaining the focus or place for the sensitive plate. For if the collodion film be put where the image on ground glass seems best defined, the resulting photograph will not be sharp, because the actinic rays do not form their image there, but either farther from or nearer to the lenses, depending on the amount of the chromatic correction given by the optician. Practically by repeated trials and variation of the place of the sensitive compound, an approximation to the focus of the rays of maximum photographic intensity is reached.

Fig. 47.



Microscope for Photography.

During my father's experiments on light, and more particularly when engaged in the invention of portrait photography, he found that the ammonio-sulphate of copper, a deep blue liquid, will separate the more refrangible rays of light, the rays

concerned in photography, from the rest. If a beam of sunlight be passed through such a solution, inclosed between parallel plates of glass, and then condensed upon an object on the stage of a microscope, a blue colored image will be formed on the ground glass, above the eyepiece. If the place of best definition be carefully ascertained, and a sensitive plate put in the stead of the ground glass, a sharp photograph will always result.

Besides, there is no danger of burning up the object, as there would be if the unabsorbed sunlight were condensed on it, and hence a much larger beam of light and much higher powers can be used. The best results are attained when an image of the sun produced by a short focussed lens is made to fall upon and coincide with the transparent object. In 1856 we obtained photographs of frog's blood disks, navicula angulata, and several other similar objects under a power of 700 diameters, excellently defined. Since then several hundreds of microscopic pictures have been taken.

In the figure, *a* is the heliostat, *b* a lens of three inches aperture, *c* the glass cell for the ammonio-sulphate of copper, *d* the object on the stage of the microscope *e*, *f* the camera for the ground glass or sensitive plate. Above the figure the course of the rays is shown by dotted lines.

In concluding this account of a Silvered Glass Telescope I may answer an inquiry which doubtless will be made by many of my readers, whether this kind of reflector can ever rival in size and efficiency such great metallic specula as those of Sir William Herschel, the Earl of Rosse, and Mr. Lassell? My experience in the matter, strengthened by the recent successful attempt of M. Foucault to figure such a surface more than thirty inches in diameter, assures me that not only can the four and six feet telescopes of those astronomers be equalled, but even excelled. It is merely an affair of expense and patience. I hope that the minute details I have given in this paper may lead some one to make the effort.

HASTINGS, WESTCHESTER COUNTY,
NEW YORK, 1863.

Postscript.—Since writing the above I have completed a photograph of the moon 50 inches in diameter. The original negative from which it has been made, bears this magnifying well, and the picture has a very imposing effect.

PUBLISHED BY THE SMITHSONIAN INSTITUTION,

WASHINGTON CITY,

JULY, 1864.

SMITHSONIAN CONTRIBUTIONS TO KNOWLEDGE

PART OF VOLUME XXXIV

ON THE MODERN REFLECTING TELESCOPE, AND THE MAKING AND TESTING OF OPTICAL MIRRORS

BY

GEORGE W. RITCHEY

ASSISTANT PROFESSOR OF PRACTICAL ASTRONOMY, AND SUPERINTENDENT OF INSTRUMENT CONSTRUCTION, IN YERKES OBSERVATORY

(No. 1459)

CITY OF WASHINGTON

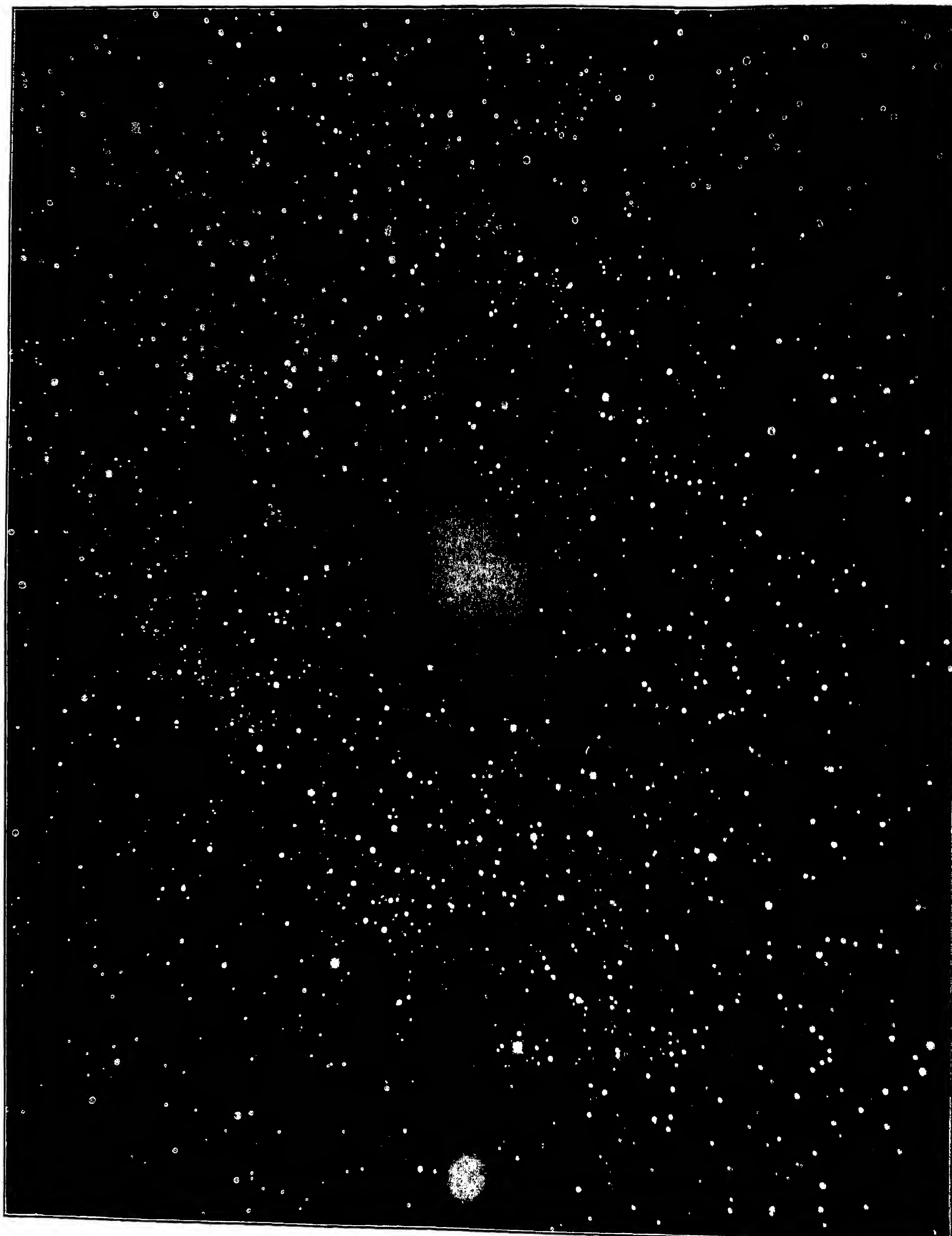
PUBLISHED BY THE SMITHSONIAN INSTITUTION

1904

CONTENTS.

LIST OF ILLUSTRATIONS.

NORTH



CENTRAL PART OF GREAT NEBULA IN ANDROMEDA. PHOTOGRAPHED BY G. W. RITCHEY, YERKES OBSERVATORY. TWO-FOOT REFLECTOR.

Enlarged 5.26 times from original negative.

ON THE MODERN REFLECTING TELESCOPE, AND THE MAKING AND TESTING OF OPTICAL MIRRORS.

By G. W. Ritchey.

INTRODUCTION.

The present paper describes the methods employed by the writer in the optical laboratory of the Yerkes Observatory in making and testing spherical, plane, paraboloidal, and (convex) hyperboloidal mirrors. On account of the very great importance of supporting mirrors properly in their cells when in use in the telescope, a chapter is devoted to the description of an efficient support system for large mirrors. Intimately related to this, and equally important, is the subject of the mounting—the mechanical parts—of a modern reflecting telescope; accordingly, the final chapter is devoted to a consideration of this subject.

CHAPTER I.

DISKS OF GLASS FOR OPTICAL MIRRORS.

No greater mistake could be made than to assume that cheap and poorly annealed disks of glass, or those with large striæ or pouring marks, are good enough for mirrors of reflecting telescopes. While I am not prepared to say that optical glass of the finest quality must be used for mirrors in order to secure the best attainable results, it is evident that a very high degree of homogeneity and freedom from strain is necessary in order that the figure of mirrors shall not be injuriously affected by changes of temperature. If it were not necessary to consider the question of cost, I should advise the use of the finest optical (crown) glass always, in order to be as free as possible from risk; usually considerations of cost would, in the case of large mirrors, make it necessary to choose between such an optical disk of a given size and a somewhat larger one of the kind furnished by the St. Gobain

Company, for example. The diagonal plane mirror of a Newtonian, and the convex mirror of a Cassegrain reflector, should always be made of the best optical glass, since the expense for these is comparatively slight.

The writer has used many disks made at the celebrated glass-works of St. Gobain, near Paris, of sizes from 8 inches in diameter and $1\frac{1}{2}$ inches thick, to the great one shown in the plates accompanying this article, which is 5 feet in diameter and 8 inches thick, and which weighs a ton. All of these disks are beautifully free from bubbles and large striæ, and are fairly well annealed, considering their great thickness. It is a most encouraging fact that the quality of the 5-foot disk is not inferior in any respect to that of disks of 8, 12, 20, 24, and 30 inches diameter which I have used. The makers of the 5-foot disk have recently expressed their readiness to undertake for us a 10-foot disk, one foot thick, which they think could now be made as perfect in all respects as the 5-foot disk. In ordering these disks it is always specified that great care be given to thorough stirring and thorough annealing. I have no doubt that in the case of very large and thick disks the makers could be prevailed upon to give even greater care to these points than is now given.

A very important point is in regard to the best thickness of optical mirrors. As a result of experience in making and using many mirrors of 24 and 30 inches diameter, in which the thickness of the several disks varies from one-twelfth to one-sixth of the diameter, I have no doubt that the thicker disks are always preferable, provided that they are as homogeneous and well-annealed as the thinner ones. The thinner mirrors suffer much greater temporary change of curvature from the very slight heat generated during the process of polishing; and they are undoubtedly more liable to suffer temporary disturbance of figure from changes of temperature when in use in the telescope. In the cases of the large paraboloidal mirror of a reflecting telescope, and the large plane mirror of a coelostat or heliostat, which should always be supported at the back to prevent flexure, the thickness should not be less than one-eighth or one-seventh of the diameter; in the writer's opinion the latter ratio leaves nothing to be desired. In the cases of the small diagonal plane mirror and the small convex mirror, which cannot easily be supported at the back, the thickness should be not less than one-sixth of the diameter.

All mirrors should be polished (not figured) and silvered on the back as well as on the face, in order that both sides shall be similarly affected by temperature changes when in use in the telescope; for the same reason the method of supporting the large mirror at the back, in its cell, should be such that the back is as fully exposed to the air as possible.

CHAPTER II.

THE OPTICAL LABORATORY OF THE YERKES OBSERVATORY.

A LARGE, well-lighted room, 70 feet long by 20 feet wide, in the north basement of the Observatory, was designed for the optical laboratory. The floor,

FIVE-FOOT MIRROR AND GRINDING MACHINE.
SHOWING METHOD OF TIPPING GLASS ON EDGE FOR TESTING.

which is nearly on a level with the ground outside, is of cement and is heavily painted. The walls are of brick, are about two feet thick, and are covered with two layers of heavy ceiling paper arranged so as to give two tight one-inch air-spaces for constant-temperature purposes. All joints of the paper are lapped and are nailed down with strips of wood. The ceiling of the room is heavily varnished.

The large room is divided into three rooms connected by large doors; these doors are so arranged that the entire length of the large room and of a wide hall opening from it, making an apartment 165 feet long, can be utilized for testing. The east and middle rooms of the three are used for grinding and polishing. The large windows of these rooms are fitted with storm sash on the inside; these are built in permanently and are made air-tight by means of ceiling paper. The west room contains the motor which supplies power to the grinding and polishing machines in the inner rooms; power is transmitted by a long shaft which runs the entire length of the rooms; this shaft is built in air-tight (to prevent dust) beneath the long work-bench which runs along one side of the rooms.

With these arrangements temperature, moisture, and freedom from dust can be controlled in the grinding and polishing rooms with all necessary refinement. In other respects, however, three great improvements could be made in planning an ideal optical shop; two of these relate to the comfort and health of the optician. First, the rooms should be arranged so that direct sunlight could be admitted to them during all parts of the optical work in which this would not be injurious to the work itself. Second, provision should be made for supplying to the rooms an abundance of fresh air, of a definite temperature, and washed free from dust. Third, for constant-temperature purposes, walls and partitions covered with a heavy layer of asbestos plaster (commercially termed Asbestic) would be preferable, on account of the superiority of the insulating and fire-proofing qualities of this material, to those of ceiling paper with air-spaces.

CHAPTER III.

GRINDING AND POLISHING MACHINES.

The grinding and polishing machines used by the writer are somewhat similar in principle to Dr. Draper's machine, shown in Fig. 25 of his book, but are more elaborate. I shall describe here the machine used in making the 5-foot mirror, both because it embodies most of the essential features of a grinding and polishing machine, and also because it is the only one of my machines of which I have a series of photographs for illustration. A good idea of this machine may be gained from the views of it shown in Plates II, III, IV, and VI.

The massive turntable upon which the glass rests consists of a vertical shaft or axis five inches in diameter, carrying at its upper end a very heavy triangular casting, upon which, in turn, is supported the circular plate upon which the glass lies. This plate is of cast-iron, weighs 1,800 pounds, is 61 inches in diameter,

is heavily ribbed on its lower surface, and is connected to its supporting triangle by means of three large leveling screws. The surface of the large plate was turned and then ground approximately flat; two thicknesses of Brussels carpet are laid upon this, and the glass, with its lower surface previously ground flat, rests upon the innumerable springs formed by the looped threads of the carpet. No better support for a glass during grinding and polishing could be desired.

Three adjustable iron arcs at the edge of the glass serve for centering the latter upon the turntable, and prevent it from slipping laterally.

The entire turntable, with the heavy frame of wood and metal which supports it, can be turned through 90° about a horizontal axis, thus enabling the optician to turn the glass quickly from the horizontal position which it occupies during grinding and polishing, to a vertical position for testing. This is shown in Plate II.

The turntable is slowly rotated on its vertical axis by means of the large pulley below (Plate III). This rotation is effected by means of belting from the main vertical crank-shaft on the east end of the machine; this shaft is well shown at the left in Plate IV. At the upper end of this shaft is the large crank, with adjustable throw or stroke, which moves the large and strong main arm to which the grinding and polishing tools are connected, and by means of which they are moved about upon the glass. This I shall always refer to as the main arm. It is a square tube of oak wood, and is strong enough to carry the counterpoising lever shown in Plate IV, and the weight of any of the grinding tools, when fully or partially counterpoised. This main arm also carries the system of pulleys and belts by which the slow rotation of the grinding and polishing tools is rigorously controlled; these, and the manner in which this rotation is effected, are well shown in Plate IV.

The west end of the main arm consists of a strong steel shaft which slides in a massive bronze swivel-bearing which corresponds to the "elliptical hole in the oak block *p*" of Dr. Draper's machine (see his Fig. 25). But this bearing is not stationary as in Draper's machine; it is not only mounted on a long slide (which I shall refer to throughout this article as the transverse slide), so that it can be slowly moved for several feet across the west end of the machine by means of a long screw, but this bearing and slide are carried upon a secondary strong arm, which is moved by a secondary crank at the southwest corner of the machine. Unfortunately there is no photograph which shows this part of the machine as it appears when in use; Plates II and III show the secondary crank well, but the secondary arm is shown swung around with one end resting on a bracket on the wall, in order to have it out of the way.

The arrangement of the west end of the machine is the result of experience with several machines, and is found extremely serviceable and convenient. The long transverse slide on the secondary arm allows the grinding and polishing tools to be placed so as to act on any desired zone of the glass, from the center to the edge; and this setting can be changed as desired while the machine is running. The secondary crank, which turns at the same speed as the large one which drives the main arm, enables the optician to change as desired the width of the (approximately) elliptical stroke or path of the tool with reference to the length of this

FIVE-FOOT MIRROR AND GRINDING MACHINE.
SHOWING LEVER FOR HANDLING HEAVY GRINDING AND POLISHING TOOLS.

stroke; this change is especially desirable when figuring the glass; it is, of course, impossible when only one driving-crank is used.

I regard the transverse slide, or something equivalent to it, as absolutely necessary to the success of a grinding and polishing machine; it will be noticed that its purpose corresponds, in some measure, to that of the long slot in the main arm of Draper's machine; I have used both arrangements and have found the transverse slide to be far more effective and convenient in use; its use will be described in the chapters on grinding and polishing.

The secondary crank, while very desirable and convenient, for the reason given above, is not indispensable; I have used several smaller machines which have given good results without it.

The manner in which the grinding and polishing tools are connected to the main arm is shown in Plate IV. A vertical shaft, $1\frac{3}{8}$ inches in diameter and 24 inches long, both rotates and slides (vertically) freely in bronze bearings attached to the main arm. The grinding and polishing tools are connected to the lower end of this shaft through the medium of a large universal coupling,—a gimball or Hooke's joint,—with two pairs of horizontal pivots at right angles to each other; this allows the tools to rock freely in all directions in order to follow the curvature of the glass. The tools are lifted, for counterpoising them, by the lever above (see Plate IV), through the medium of the vertical shaft and the universal coupling. In the case of very massive grinding tools of moderate size, like that shown in this illustration, the universal coupling is connected directly to the back of the tool; but in the case of all large tools which are to be used for fine work this connection is made through the medium of a system of bars and triangles, so that the tools are counterpoised without the slightest danger of changing their shape. A small coupling with ball bearings at the upper end of the vertical shaft allows the latter to rotate freely with reference to the link which connects it to the counterpoise lever.

To recapitulate briefly: this method of connecting the grinding and polishing tools allows them to be controlled in all of the following ways simultaneously: (1) the stroke of the tool is given by the motion of the main arm; (2) the slow rotation of the tool is rigorously controlled by the belting above; (3) the tool is allowed to rock or tip freely by means of the universal coupling, in order that it may follow the curvature of the glass; (4) the tool rises and falls freely by means of the sliding of the $1\frac{3}{8}$-inch vertical shaft in its bearings, in order that it may follow the curvature of the glass; (5) the tool is counterpoised by means of the lever on the main arm, through the medium of the same vertical shaft and universal coupling.

In Plate III is shown the large lever by which the 5-foot glass, which weighs a ton, is lifted on and off the machine, and by means of which, also, the large grinding tools are handled. One of the full-size grinding tools, weighing 1,000 pounds, is shown suspended by the lever. The arrangements are so convenient that the optician alone can do all parts of the work.

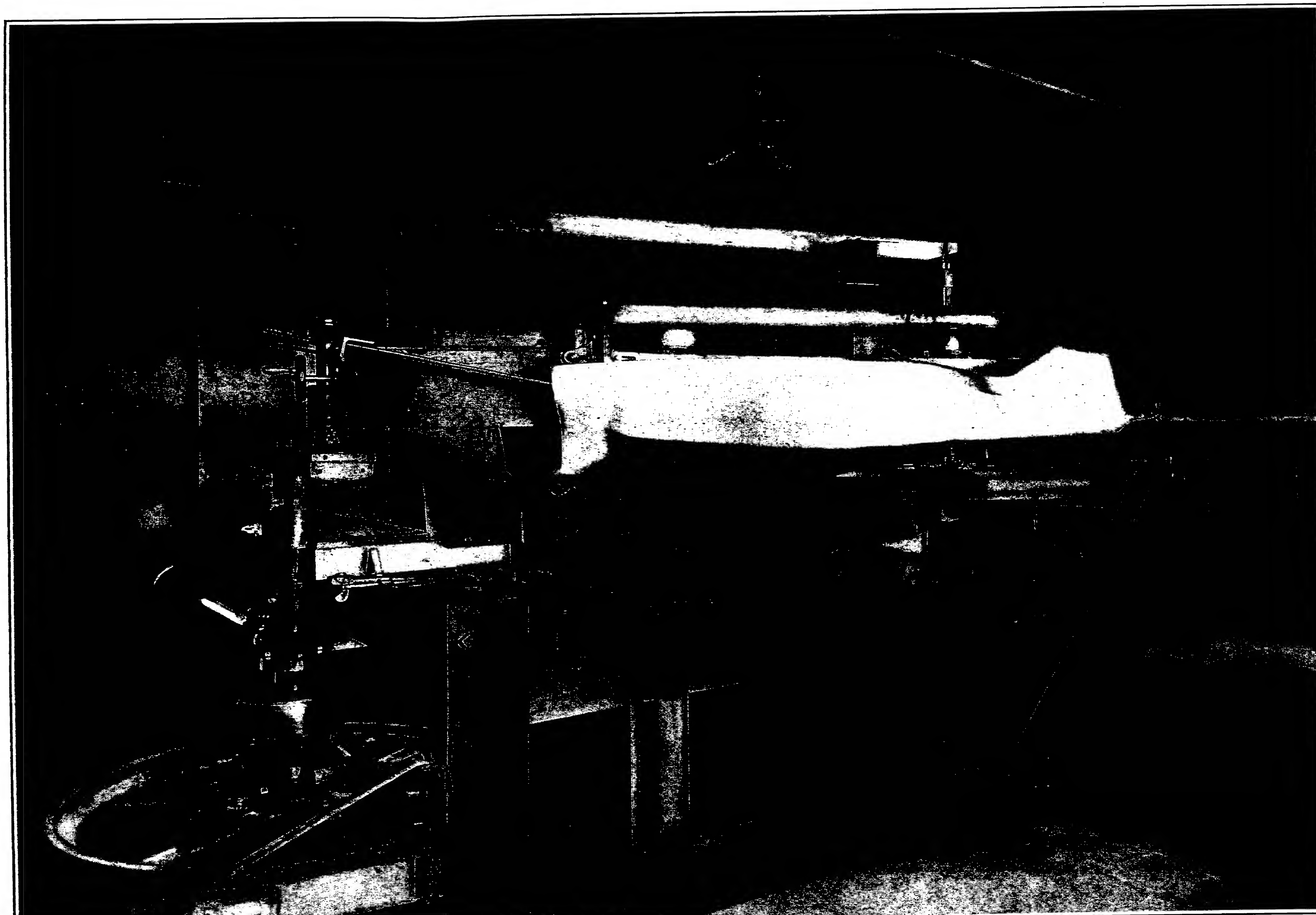
CHAPTER IV.

GRINDING TOOLS.

While grinding tools of glass were used in much of my earlier work, and are still used for small work, I now use cast-iron grinding tools for all large work. These are cast very heavy, with ribs on the back; the ribs are made heavy, but not deep (or high). For large work iron tools are cheaper than glass ones; they are more easily prepared; they are more easily and safely counterpoised, which is always necessary in the fine-grinding of large work; and they produce on the glass a fine-ground surface fully as smooth and perfect as can be obtained with glass tools.

An important question is in regard to the size of grinding tools,—whether they should be of the same diameter as the mirror. For mirrors up to 24 or 30 inches in diameter full-size tools are generally used. For concave mirrors larger than 30 inches in diameter I use grinding tools whose diameter is slightly more than half that of the glass, *i. e.*, a 16-inch tool for a 30-inch glass; a 32-inch tool for a 60-inch glass. These I shall refer to as half-size tools. Full-size tools are, of course, much more expensive and difficult to make; they are many times heavier than half-size tools of equal stiffness; and they require a much stronger grinding machine to counterpoise them properly; grinding can be done with them, however, more quickly than with the smaller tools. Half-size tools are economical and are quickly prepared; they are easily counterpoised; and a much greater variety of stroke can be used with them, so that with a well-designed grinding machine I have found it easier to produce fine-ground surfaces, entirely free from zones, with half-size than with full-size tools. If temperature conditions and uniform rotation of the glass are carefully attended to, the surface of revolution produced by the smaller tools is fully as perfect as that given by the larger ones; I always take the precaution, however, to work a full-size approximately flat tool on the glass before beginning to excavate the concave, so as to start out with a surface of revolution.

Grinding tools for concave and convex mirrors are always made in pairs, one concave, the other convex. Grinding tools for plane mirrors are made in triplicate. These iron tools, when being cast, are "poured" face down, so that the faces will be clean. I shall describe the preparation of a pair of iron tools for a concave mirror, leaving the description of tools for plane mirrors until the making of plane mirrors is discussed. The convex and concave tools are turned in a lathe to the proper curvature as shown by templets. The convex tool, which is, of course, to be used on the concave glass, is now placed on a planing machine, and has a series of grooves cut across the convex surface. These grooves are usually ¼ inch wide, and run in two directions at right angles to each other; these divide the surface into squares, which are usually made about one inch on a side. These grooves serve to distribute the grinding material uniformly, and entirely obviate the tendency of the tools to cling to the glass in fine-grinding. No grooves are cut in the concave tool. A number of holes are now bored through both tools, in such positions that wooden cups or funnels can be inserted into the holes from the back or ribbed side



FIVE-FOOT MIRROR AND GRINDING MACHINE.
SHOWING HALF-SIZE GRINDING TOOL SUSPENDED ON MAIN ARM.

of the tool, without interfering with the ribs; these cups serve for the introduction of the grinding material during the process of grinding; they should be thoroughly varnished.

The convex and concave tools are now ground together on the machine, with fine grades of carborundum (which is much more effective for this purpose than emery) and water. This eliminates the circular marks left by the lathe, and enables the optician to secure the exact curvature desired. A very important point is that by grinding with the concave tool on top, the radii of curvature of both tools can be gradually shortened; when the convex tool is used on top the curvature of both is gradually flattened. By this means, and the use of very fine grades of carborundum, a most perfect control of the curvature of the tools may be had.

The curvature of the tools and of the glass is measured by means of a large spherometer; this is shown in Plate v, resting upon a 12-inch glass grinding tool. The spherometer is of the usual three-leg form; the legs terminate in knife-edges, the lines of which are parts of the circumference of a 10-inch circle. The central screw is very carefully made; it was ground in its long nut (which was made adjustable for tightness) with very fine grades of emery such as are used in optical work; screw and nut were then smoothed and polished by working them together with rouge and oil. The screw is of $\frac{1}{2}$ millimeter pitch, and the head, which is 4 inches in diameter, is graduated to 400 divisions. On fine-ground surfaces settings can be made to one-half or one-third of a division, corresponding to a depth of $\frac{1}{40000}$ or $\frac{1}{60000}$ of an inch, approximately.

CHAPTER V.

POLISHING TOOLS.

After experience with polishing tools of various kinds, the tools which I now use exclusively for large work consist of a wooden disk or basis constructed in a peculiar manner, and covered on one side with squares of rosin faced with a thin layer of beeswax. The wooden disk may be replaced, in the case of small polishing tools up to 12 or 15 inches diameter, by a ribbed cast-iron plate so designed as to be extremely light and rigid; the bases of larger tools may be made of cast aluminum, but this, in order to be strong and rigid, must contain 15 % or more of other metals; such a basis for a 30-inch polishing tool weighs about sixty pounds, and the rough casting alone costs about fifty dollars. It is possible that a metal basis possesses an advantage over a wooden one in that its surface is less yielding. Tools properly constructed of wood, however, are light and extremely rigid, are easily made, and are economical in cost. As their proper construction is a matter of the utmost importance, I shall describe, somewhat in detail, the method of making wooden bases of from 15 to 40 inches diameter.

A large number of strips of dry and straight-grained pine wood $1\frac{1}{4}$ inches wide and $\frac{5}{16}$ inch thick are prepared; the wooden basis is built up of successive layers

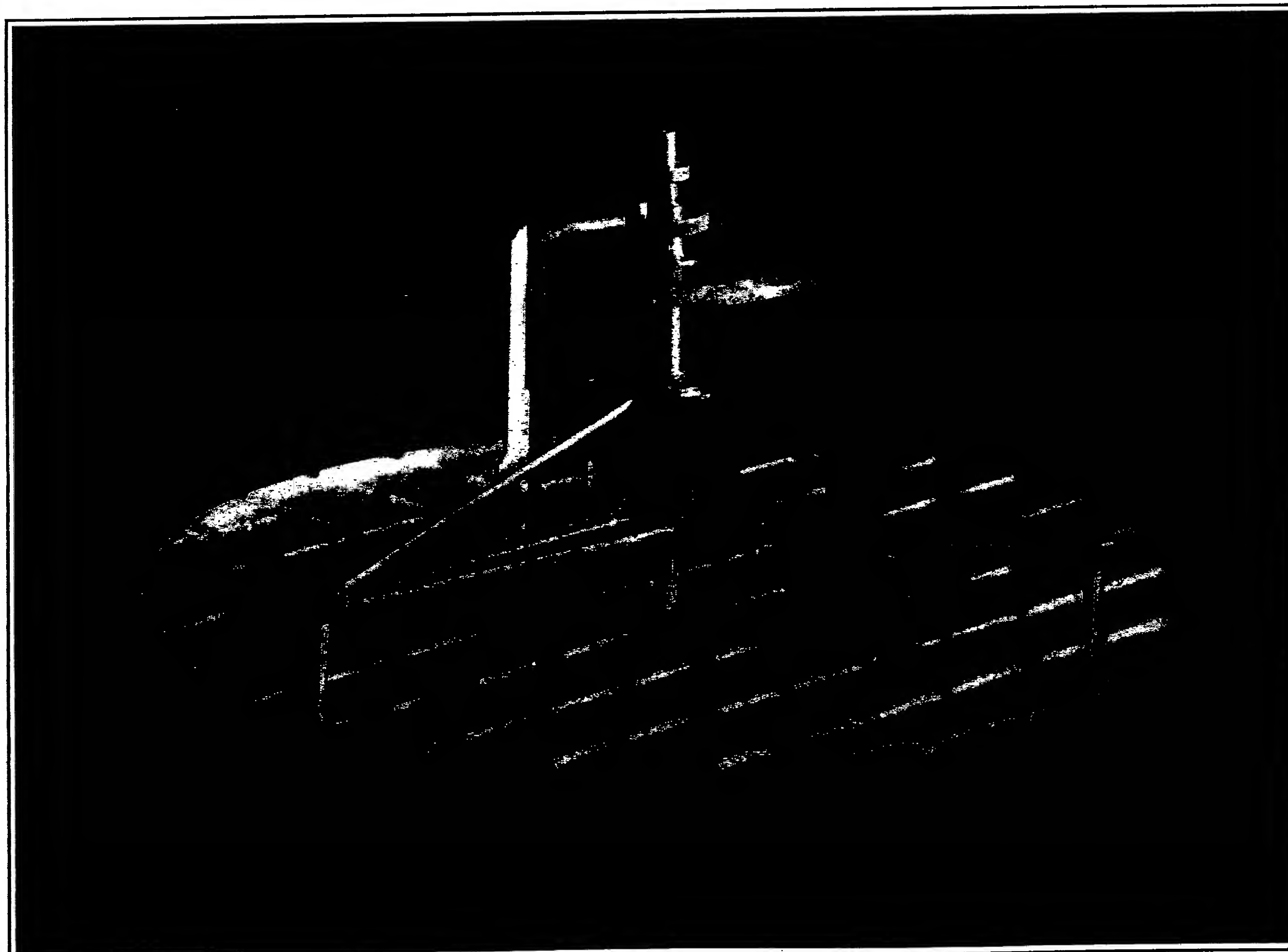
of these strips. The strips in all layers except the two outer ones are laid just $\frac{1}{4}$ of an inch apart. Those of each layer are placed at right angles to those of the next layer below, and are glued and nailed down with long wire brads. The best cabinet-maker's glue is used, and the strips are warmed before the glue is applied. Each crossing of the strips in the successive layers (*i. e.*, each of the $1\frac{1}{4}$-inch squares), is nailed with at least two nails. The upper surface of each layer is carefully planed flat before the next layer of strips is applied. For a 20-inch tool six layers of pine strips (each $\frac{5}{16}$ inch thick) are used; for a 24-inch tool, seven layers; for a 36-inch tool, ten layers. Next, one layer of thoroughly seasoned strips of hard straight-grained cherry wood about $\frac{5}{8}$ inch thick and slightly less than $1\frac{1}{2}$ inches wide is added, to form the outer layer at the back of the tool; these strips are laid almost touching each other. In the case of tools for flat mirrors, a precisely similar layer of cherry strips is added to form the outer layer at the front or face of the tool. But in the case of tools for concave or convex mirrors the strips composing the front layer must be made thicker, to allow for the curvature of the face of the tool. If this curvature is great, the cherry strips forming the front layer are made of double width (*i. e.*, slightly less than 3 inches wide), in order that the width of their bases shall be greater as compared with their thickness; this is usually done when the depth of the curve is greater than $\frac{1}{4}$ inch. The gluing and nailing of the outer layers of strips are done with the greatest thoroughness, four of the long fine nails being driven through into each of the squares of pine wood beneath. For tools less than 20 inches in diameter thinner strips and a larger number of layers are used. The entire thickness of the wooden disk or basis built up in this way should be between one-tenth and one-eighth of its diameter.

This wooden basis is next placed in a large lathe, the edge is turned smooth and to the proper diameter, and the face is turned to fit the curvature of the glass to be polished.

A round pan of galvanized iron large enough to contain the wooden disk having been prepared, enough hard paraffin is melted in it so that the disk can be soaked in the liquid paraffin; the latter must not be hotter than 150° Fahrenheit, otherwise the strength of the glue-joints will be injured. It is best to melt the paraffin on a gas or gasoline stove, so that the degree of heat can be easily controlled. The tool should soak for several hours, being moved continually and turned over often. Since the construction of the wooden basis is such that a great number of openings extend entirely through it, the melted paraffin permeates the entire tool thoroughly. The wooden tool prepared in this way is lighter than any metal tool of the same degree of stiffness, and is entirely impervious to the moisture which is necessary in the polishing room. The question of lightness is a most important one, as will be seen when the work of polishing is described later.

The front or face of the wooden basis is now lightly scraped with a wide, sharp chisel, to remove any excess of paraffin, and is then marked off for $1\frac{1}{4}$-inch squares of rosin, with grooves $\frac{1}{4}$ inch wide between them; the grooves should come exactly above the $\frac{1}{4}$-inch spaces left between the pine strips beneath.

The preparation of the rosin squares is usually a very troublesome matter, but



LARGE SPHEROMETER ON TWELVE-INCH GLASS GRINDING TOOL.

becomes easy when the following directions are observed. A clean, flat board, having an area about twice that of the polishing tool, is prepared. One face of this is covered with clean paper. Long strips of wood $\frac{1}{4}$ inch square are fastened upon the paper by means of fine brads; these strips are placed just $1\frac{1}{4}$ inches apart, and the ends of the grooves thus formed (grooves $1\frac{1}{4}$ inches wide, $\frac{1}{4}$ inch deep, and of any convenient length) are closed with strips of wood. The board is now carefully leveled. The rosin, when melted and softened to the proper degree, is to be poured into these grooves, which serve as moulds.

A quantity of rosin sufficient to fill all of the grooves is melted in a clean pan. Even when only a small quantity is needed it is best to melt at least ten pounds of rosin, since the entire process of "tempering" and pouring is more easily and satisfactorily carried on with large quantities than with small. Only lumps of clear, clean rosin should be used. A gas or gasoline stove is very convenient for melting the rosin, since the degree of heat can be easily controlled. When the rosin is melted the pan is removed from the stove and a quantity of turpentine, equal in weight to about $\frac{1}{25}$ of the rosin used, is added, and the mass thoroughly stirred. A tablespoonful of the liquid is now dipped out and immersed for several minutes in a bucket of water at the temperature of the polishing room, which should be about 68° Fahrenheit. The spoonful of rosin is now taken out, and its hardness tried with the thumb-nail. If the rosin is brittle at the thin edges it is still too hard, and a little more turpentine must be added; if, however, it is soft like wax or gum, it is too soft, in which case the pan of rosin must be hardened by boiling for a few minutes; this drives off the excess of turpentine. When the rosin is of the proper hardness an indentation about $\frac{1}{4}$ inch long can be made in it by moderate pressure of the thumb-nail for five seconds. When the proper degree of hardness has been obtained it is often necessary to heat the pan of rosin again so that it will not be too thick to pass readily through the strainer; this is a long, narrow bag of cheese-cloth through which the rosin is strained as it is being poured into the grooves or moulds previously described. If such heating is necessary it must be done gently and without boiling; otherwise the rosin will be hardened. Enough is poured into each groove to just fill it.

After being poured, the rosin should cool for six or eight hours. Then the nails which held the quarter-inch strips of wood to the board below are removed, and the layer of rosin, wooden strips, and paper is carefully lifted from the board, when the paper is easily stripped from the rosin, to which it does not adhere closely. With care the thin strips of wood can now be removed, one after the other, and the long strips of rosin, $1\frac{1}{4}$ inches wide and $\frac{1}{4}$ inch thick, are secured without chipping or breaking. These are now readily cut into squares with a hot knife.

The squares are attached to the previously marked wooden basis by quickly warming one face of each square over a flame and then pressing it gently against the tool with the fingers. The tool is now ready for rough-pressing.

Three strong eyes are screwed into the back of the tool, and it is suspended, face down (by means of wires connected to the ceiling of the room), so as to hang

about two feet above the flame of a gas or gasoline stove. The tool can now be swung about so that the rosin squares are warmed uniformly. When the squares are slightly soft and very slightly warm, *but not hot*, to the touch, the tool is placed upon the previously ground glass which is to be polished, the glass having just previously been thoroughly wet with distilled water so that the rosin will not stick to it. Slight pressure may be exerted to assist in pressing the rosin surface to fit the glass. The tool will have to be slightly warmed and pressed several times before good contact is secured all over. I always prefer to "rough-press" the rosin tools on an iron grinding tool having the same form as the glass, if a sufficiently large one is available; but the precaution is always taken to cover the iron tool with clean wet paper.

The rosin squares will have spread somewhat irregularly during the rough-pressing; so the surface is marked with a straight-edge and knife, and the edges of the squares are trimmed so that the grooves between them are straight and of uniform width. This trimming is best done with a sharp knife, held so as to make an angle of about 60° with the surface of the tool, and drawn quickly toward the workman.

The rosin squares are now ready for coating with wax. A pound of best beeswax is melted in a large clean cup and is very carefully strained through several thicknesses of cheese-cloth into a similar clean cup. A brush is made by tying several thicknesses of cheese-cloth around the end of a thin blade of wood $1\frac{1}{4}$ inches wide. Each rosin square is now coated with a thin layer of wax, by a single stroke of the brush; the wax should be very hot, otherwise the layer will be too thick.

The tool is now ready for "cold-pressing" or "fine-pressing," a matter of the most vital importance, which will be more properly described later, in connection with the work of polishing the glass.

The work of making a large concave mirror will now be described in detail.

CHAPTER VI.

ROUGH-GRINDING THE FACE AND BACK OF A ROUGH DISK OF GLASS, AND MAKING THE SAME PARALLEL.

THE rough disk of glass is placed upon the carpeted turntable, and a long strip of thin oilcloth is drawn around its edge; the upper edge of the oilcloth is securely fastened to the glass by means of a strong cord, and the junction between oilcloth and glass is made water-tight by means of water-proof adhesive tape. The oilcloth strip is wide enough to hang several inches below the edge of the iron plate on which the glass rests, so that the circular trough of galvanized iron, which can be seen in Plates IV and VI, catches all of the emery and water which are washed over the edges of the glass during grinding; this circular trough is stationary, has two holes in its bottom above the buckets, which can be seen in the plates,

and is kept scraped clean by two scrapers which reach down into it from the revolving turntable. Several important results are thus secured: the carpet cushion under the glass is kept dry; the entire machine is kept perfectly free from the dripping of the grinding material; and all of the latter material is caught in buckets and is used again and again in the later and finer grinding.

The large irregularities of surface of large rough disks are usually ground away with coarse emery and a heavy, flat, half-size iron tool without grooves, the surface of which is rounded up considerably at the edge, so that the tool may rise easily over obstructing irregularities without breaking them. The grinding machine is set so that the half-size tool moves over the glass well out to one side of the latter; the rotation of the turntable of course brings all parts of the glass in succession under the tool; if the setting of the machine is such that the half-size tool passes in much beyond the center of the glass at every stroke, the surface of the latter will become concave.

When the marked irregularities of surface are ground away, the full-size, flat, grooved iron tool is put on. A tool of this kind is almost indispensable in making a mirror. Emery and water are supplied through the cups at the back of the tool, and the glass is quickly ground approximately flat. The glass is now turned over, and the other side is ground in a precisely similar manner.

The thickness of the glass is now tried, all around, by means of calipers. The approximately flat surfaces will probably be found to be far from parallel. If this is the case, the thick side may be ground down as follows: The belt which drives the turntable is loosened, until it will just rotate the latter, and a brake is arranged so that the workman can stop the rotation of the turntable at any desired point by pressing on the brake with his foot. A flat, half-size grooved tool is put on, and set so as to work far out to one side of the glass. A medium grade of emery (No. 70) is used, and the machine started. As the thick side of the glass, which has been marked, comes beneath the moving tool, the turntable is slowed down or stopped, so that a great excess of grinding is done on the thick side at each revolution. By distributing the grinding carefully, and trying the thickness often with the calipers, the upper surface is easily made parallel to the lower one. When this is done the full-size tool is again used for a short time. The glass is then ready for edge-grinding.

CHAPTER VII.

GRINDING EDGE OF GLASS.—ROUNDING OF CORNERS.

In order that an efficient edge-support, which will be described later, may be given to the glass, it is desirable that the edge of the latter be ground truly circular and square with the face. The manner in which this is accomplished is shown in Plate VI. The glass lies upon three large blocks of wood, which hold it several

inches above the surface of the circular iron plate. Thin oilcloth is arranged about the blocks and over the iron plate, to keep them dry. A smooth, flat, iron face-plate is mounted (so as to rotate in a vertical plane) on a heavy lathe head-stock; the latter is carried upon a strong slide which can be moved toward the glass by means of a fine pushing-screw. The lathe and face-plate are driven at a high rate of speed by means of a belt. In the case of the 5-foot glass the face-plate used was 24 inches in diameter and made 1,000 revolutions per minute. For a 24-inch glass, $3\frac{1}{2}$ inches thick, a face-plate 11 inches in diameter, making 1,800 revolutions per minute, is used. A frame of wood, covered with oilcloth, is built around the face-plate, so that the grinding materials will not be thrown about the room. The glass rotates slowly with the turntable, as usual. Emery and water, or sand and water, are heaped upon the horizontal surface of the glass, and are slowly scraped toward and over the edge, so as to come between the revolving face-plate and the glass; a small jet of cold water, brought from the hydrant by means of a rubber tube, greatly assists in the uniform feeding of the emery, and also in preventing the generation of heat. But there is in reality no danger of heating, for the revolving face-plate *never actually touches the glass.* As the irregularities of the edge are ground away the face-plate is gradually moved forward by means of the slide and pushing-screw.

If the edge of the rough disk be very irregular, as is usually the case, the surface of the iron face-plate will have a circular groove worn in it, by the time the rough-grinding of the edge is done; in this case the face-plate should be turned flat and true again, and smoothed on a flat iron grinding-tool, before the edge of the glass is fine-ground. Several fine grades of emery are now prepared by the process of washing to be described later, and the edge-grinding is finished by the use, in succession, of three such grades of emery as flour, three-minute washed, and ten-minute washed. Care should be taken throughout the process that the edge of the glass is ground square with the face; any error in this respect can be corrected by slightly raising or lowering the outer end of the slide which supports the lathe head-stock.

Edge-grinding is accomplished very quickly in the manner described. The edge of a 24-inch disk four inches thick, even when very rough and irregular, has been ground and smoothed in ten hours of actual grinding. Despite the great speed of the rotating face-plate, I have never had any chipping of the glass or accident of any kind occur.

Before beginning the fine-grinding of the face and back it is well to round the corners at the edge of the glass. This is done by means of a smooth flat strip of sheet-brass of the size and shape of a large flat file; this is worked over the corners of the glass by hand, while the disk rotates slowly, emery and water being used for cutting. A "quarter-round" corner is usually made. Finer and finer grades of emery are used for smoothing the quarter-round. This rounding and smoothing are very necessary, as particles of glass from a sharp or rough edge are liable to be drawn in upon the surface by the action of the grinding tool during fine-grinding.

The wooden blocks are now removed and the glass replaced upon the carpeted turntable.

CHAPTER VIII.

FINE-GRINDING AND POLISHING THE BACK OF THE MIRROR.

Before discussing the work of fine-grinding I shall describe briefly the making of the fine grades of emery. I never buy finer grades than "flour." The latter grade is used with the full-size flat grooved tool to give a moderately fine surface to the glass after the rough-grinding previously described has made the front and back approximately flat and parallel. The residue of emery, fine ground glass, and water, resulting from the grinding with flour emery, is caught in buckets, as previously described. This residue is mixed with an abundance of water, in (for a large mirror) three or four clean granite-ware buckets, which are marked *A*. The contents of these buckets are thoroughly stirred, and are allowed to settle for two minutes; during this time all coarse particles will have settled to the bottom, and "two-minute" emery and finer grades remain in suspension in the water. The liquid is now quickly siphoned off, by means of a rubber tube, into other clean granite-ware buckets marked *B*, from which the handles have been removed. The contents of the latter are allowed to settle for four minutes, when the greater part of the liquid in each is carefully poured back into the buckets *A*. The contents of the latter buckets are reserved. The sediment remaining in the buckets *B* is the "two-minute" washed emery, with which the fine-grinding of the back is begun. After the grinding with this grade is finished, the residue from this grinding is mixed with what was reserved in the buckets *A*, the whole is stirred again and allowed to settle for five minutes, the liquid is siphoned off, and thus "five-minute washed" emery is secured. In a similar manner emeries which have remained in suspension in water for 12, 30, 60, 120, and 240 minutes are secured. In this way the large quantities of the finer grades which are necessary for large work can be secured as the work progresses. If accumulations of residues from previous work are available, some time will be saved by washing out all of the fine grades desired before the fine-grinding is begun.

Plane and concave mirrors are finished approximately flat on the back, as this form is most convenient for the application of the support-system. Fine-grinding of the back is usually done with the full-size, flat grooved tool, as this works rapidly. In this part of the work, in which the greatest refinement is not necessary, it is my custom to use the fine grades of emery (when these have all been prepared in advance) in succession, without stopping the machine or taking off the tool between grades for the purpose of cleaning the tool and the glass. The emery and water are supplied through the wooden cups at the back of the tool.

For a 24-inch mirror and its full-size tool, strokes varying from 6 to 8 inches in length are used with the 2-, 5-, and 12-minute washed emeries; shorter strokes, from 4 to 6 inches in length, are used with the finer grades. Considerable lateral displacement of the tool, amounting at the greatest to 2 or 2½ inches on the glass, is given at short intervals, by means of the transverse slide. On an average 20 double strokes per minute are given in fine-grinding a 24-inch mirror with full-size tool. Between 7 and 8 double strokes occur for each revolution of the glass and turntable.

With regard to counterpoising the tools during fine-grinding, the following statements may be made: My full-size iron tools for a 24-inch mirror weigh about 150 pounds, or $\frac{1}{3}$ pound for each square inch of area. This weight, or even $\frac{1}{2}$ pound to the square inch, is not objectionable with emeries down to 5-minute or 10-minute washed; but when this weight is allowed with finer emeries, scratches are liable to occur; indeed, with 30-minute washed and all finer grades they are almost certain to occur. The pressure on the glass is therefore decreased, by counterpoising the tool, to approximately $\frac{1}{5}$ pound to the square inch for 12- to 20-minute emeries, $\frac{1}{8}$ pound per square inch for 30- to 60-minute emeries, and about $\frac{1}{12}$ pound per square inch for 120- and 240-minute emeries. *This rule is followed, approximately, in all fine-grinding, whether of back or face.* This obviates, to a great extent, the danger of scratches in grinding, provided that thorough cleanliness is practiced in the preparation and use of the fine emeries. The apparatus by which the counterpoising is effected has already been described (page 5).

In fine-grinding a 24-inch glass, the 2-minute and 5-minute emeries are used for three-quarters of an hour each; the 12- and 30-minute emeries for one hour each, and the 60-, 120-, and 240-minute emeries for one and one-half hours each. The fine-ground surface resulting is so exquisitely smooth that it takes a full polish very readily.

The back of the glass is now ready to be polished. This is done with a half-size or two-thirds size polishing tool, which is moved about on the glass by the action of the machine precisely as a half-size grinding-tool would be. Optical rouge and distilled water are used, instead of emery and water. The work of polishing will be described in detail later, in connection with the work of finishing the face of the glass.

It is an excellent plan to fine-grind and polish the front surface of a disk also, approximately flat, as has been described for the back; the optician is then able to examine carefully the internal structure of the disk. Usually there is no choice as to which side shall be used for the face of the mirror, but this can readily be determined when both sides are polished. Plate VII shows the 5-foot disk with both sides ground and polished in this manner.

CHAPTER IX.

GRINDING THE CONCAVE SURFACE.

As before stated, it is my practice to use full-size grinding tools for concave mirrors up to 24 or 30 inches in diameter. For larger concave mirrors half-size tools are generally used. I shall first describe the grinding of a 24-inch concave.

The glass must be carefully *centered* by means of the three adjustable arcs attached to the supporting plate; these arcs must not be screwed tightly against the glass, lest the latter be strained; several thicknesses of heavy drawing paper are used between arcs and glass.

With regard to counterpoising the tools during fine-grinding, the following statements may be made: My full-size iron tools for a 24-inch mirror weigh about 150 pounds, or $\frac{1}{3}$ pound for each square inch of area. This weight, or even $\frac{1}{2}$ pound to the square inch, is not objectionable with emeries down to 5-minute or 10-minute washed; but when this weight is allowed with finer emeries, scratches are liable to occur; indeed, with 30-minute washed and all finer grades they are almost certain to occur. The pressure on the glass is therefore decreased, by counterpoising the tool, to approximately $\frac{1}{5}$ pound to the square inch for 12- to 20-minute emeries, $\frac{1}{8}$ pound per square inch for 30- to 60-minute emeries, and about $\frac{1}{12}$ pound per square inch for 120- and 240-minute emeries. *This rule is followed, approximately, in all fine-grinding, whether of back or face.* This obviates, to a great extent, the danger of scratches in grinding, provided that thorough cleanliness is practiced in the preparation and use of the fine emeries. The apparatus by which the counterpoising is effected has already been described (page 5).

In fine-grinding a 24-inch glass, the 2-minute and 5-minute emeries are used for three-quarters of an hour each; the 12- and 30-minute emeries for one hour each, and the 60-, 120-, and 240-minute emeries for one and one-half hours each. The fine-ground surface resulting is so exquisitely smooth that it takes a full polish very readily.

The back of the glass is now ready to be polished. This is done with a half-size or two-thirds size polishing tool, which is moved about on the glass by the action of the machine precisely as a half-size grinding-tool would be. Optical rouge and distilled water are used, instead of emery and water. The work of polishing will be described in detail later, in connection with the work of finishing the face of the glass.

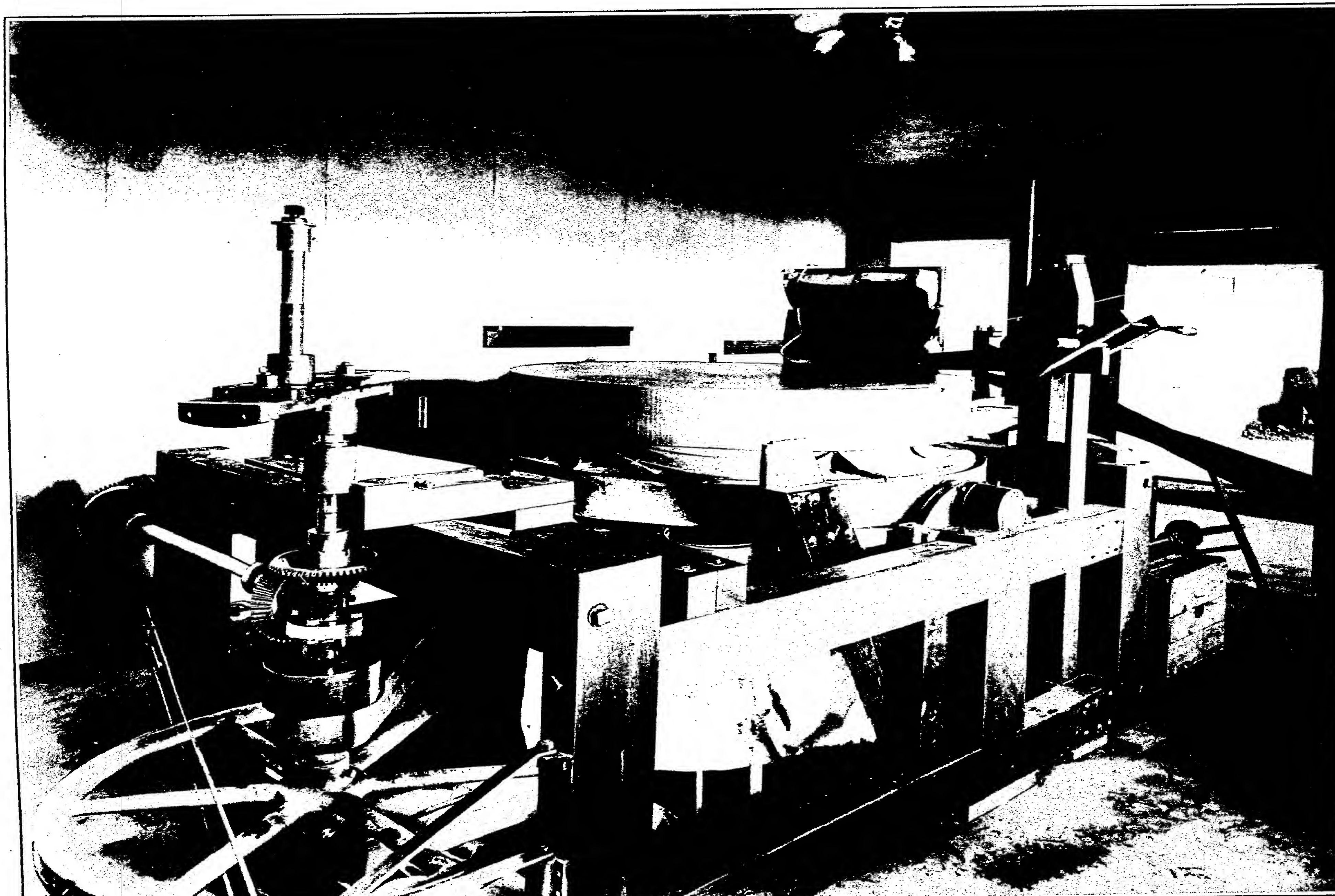
It is an excellent plan to fine-grind and polish the front surface of a disk also, approximately flat, as has been described for the back; the optician is then able to examine carefully the internal structure of the disk. Usually there is no choice as to which side shall be used for the face of the mirror, but this can readily be determined when both sides are polished. Plate VII shows the 5-foot disk with both sides ground and polished in this manner.

CHAPTER IX.

GRINDING THE CONCAVE SURFACE.

As before stated, it is my practice to use full-size grinding tools for concave mirrors up to 24 or 30 inches in diameter. For larger concave mirrors half-size tools are generally used. I shall first describe the grinding of a 24-inch concave.

The glass must be carefully *centered* by means of the three adjustable arcs attached to the supporting plate; these arcs must not be screwed tightly against the glass, lest the latter be strained; several thicknesses of heavy drawing paper are used between arcs and glass.



FIVE-FOOT MIRROR AND GRINDING MACHINE.

METHOD OF GRINDING EDGE OF GLASS.

The glass must also be carefully *levelled* (by means of the three large adjusting screws of the turntable) so that its upper surface is accurately at right angles to the axis of rotation; this is determined by rotating the turntable, and trying the surface with a surface-gauge. The band of thin oilcloth is securely bound around the edge of the glass, to keep the polished back and the cushion clean and dry.

The excavation of the concave is begun with moderately coarse emery (if the concave is to be quite deep) and a lead tool; this is a lead disk about 10 inches in diameter and $1\frac{1}{2}$ or 2 inches thick; it is easily turned in a lathe to the proper curvature; it is used on and near the center of the glass until a depression of approximately the desired curvature (as determined by the spherometer) and of 12 or 13 inches diameter is produced. A heavy iron tool about 13 inches in diameter, which has been turned and ground to the proper curvature, is now put on with about No. 90 emery. By giving careful attention to the length of stroke, and to the position of the tool on the glass as determined by the setting of the transverse slide, and by frequent trials of the curvature of the excavation with the spherometer, the diameter of the excavation is gradually increased, while its *curvature* is continually kept very near that which is desired for the finished mirror; this keeps the iron tool of proper curvature also.

The stroke used in this work should vary from 6 to 10 inches in length. As the size of the excavation increases, the setting of the transverse slide is continually changed so that the tool acts farther and farther to one side of the center of the glass; otherwise the radius of curvature will be shortened. When the diameter of the excavation has increased to about 22 inches, flour emery is substituted for the No. 90, and the grinding is continued as before. Care is now taken to make the curvature read exactly right with the spherometer. When the excavation becomes about 23 inches in diameter, the 13-inch tool is taken off, and the full-size, convex, grooved iron tool is put on; this has previously been fine-ground to the proper curvature on the corresponding concave tool. With this tool and washed flour emery the diameter of the concave on the glass is increased to $23\frac{5}{8}$ or $23\frac{3}{4}$ inches.

The fine-grinding or smoothing of the concave is now done with the full-size tool. The same grades of emery, the same lengths and speed of stroke, and the same rules in regard to counterpoising are used as have already been described in the case of fine-grinding the back of the glass (page 13). The length of stroke is changed every eight or ten minutes, and the lateral displacement of the tool (given by means of the transverse slide) is changed slightly at the end of every two or three complete revolutions of the glass. The tool is taken off after each grade of fine emery is used, and the tool and glass are carefully cleaned. With the assistance of the counterpoise lever the removal of the tool is effected easily and safely, without disconnecting it from the main arm of the machine; this is well shown in Plate IV, in which the grinding tool is shown hanging at one side of the glass.

The surface of the glass is examined with a microscope after each grade of emery is used, to make sure that no pits from previous grades remain.

During all fine-grinding and machine-polishing a large sheet of heavy clean paper or pasteboard is attached to the main arm in such a way that no particles of

dust from the belts which control the slow rotation of the tools can fall upon the glass.

The process of grinding larger concave surfaces without the use of full-size tools is precisely similar to that described for a 24-inch mirror, up to the point of substituting the 24-inch convex tool; from this point the grinding is carried on by a continuation of the use of a half-size, convex grooved tool; this may be the same iron tool which has been used for enlarging the excavation. When the diameter of the excavation approaches that of the glass, the tool should be tested with the spherometer for curvature, and, if necessary, ground in its corresponding concave iron tool until its curvature is uniform and of exactly the desired radius. The grinding of the glass is then continued with washed flour emery until the edge of the excavation is within $\frac{1}{8}$ inch of the edge. Experience in the previous use of the half-size tool, in enlarging the excavation and in keeping the curvature of the glass uniform and of the desired radius, will enable the optician to decide upon the various lengths of stroke and the various settings of the transverse slide necessary in this grinding and in the finer grinding to follow.

In fine-grinding a 30-inch concave with a 16-inch tool, strokes varying from 6 to 12 inches in length are used; for a 9-inch stroke the *normal* setting of the transverse slide (*i. e.*, one which would tend neither to lengthen nor shorten the radius of curvature of the glass) would be such that the outer edge of the tool overhangs the glass about 3 inches in the forward stroke, while the inner edge of the tool passes about one inch on the other side of the center of the glass on the return stroke.

Throughout the entire process of fine-grinding with the half-size tool the length of stroke is changed once every eight or ten minutes; at the end of every two or three revolutions of the glass the setting of the transverse slide is changed, a little at a time, for a considerable distance on either side of the *normal* setting; the setting of the slide can be changed without difficulty, while the machine is running, by merely turning a hand-wheel. By these means the formation of zones of unequal focal length can be entirely avoided.

The same grades of emery are used, and the same rules in regard to counterpoising observed, as with full-size tools. Notwithstanding the fact that the length of stroke can be considerably greater than with full-size tools, each grade of emery must be used for a longer time, on account of the smaller area of the grinding surface. Glass and tool are thoroughly cleaned, and the surface of the former examined, after the use of each grade of emery, as before described.

Care must be taken during this work that the belts which rotate the turntable are kept tight, so that no irregularity in the rotation of the turntable with reference to that of the crank-shaft can occur. It is absolutely necessary that all of the fine work on large mirrors be done in rooms where no sudden changes of temperature can occur, and that nothing be allowed which might affect the temperature of the glass locally.

If the concave mirror is intended for a paraboloidal one, the fine-ground surface should be spherical, with its radius of curvature $2\text{ F} + \frac{\text{R}^2}{4\text{F}}$, where F is the desired

focal length of the finished paraboloid and R is the semi-diameter of the mirror; the reason for this is fully explained later. I have never attempted to parabolize while fine-grinding; it is possible that it might be well to do this in the case of very large mirrors of short focus, but my practice has been to fine-grind and polish to a spherical surface, free from zones, and then to parabolize by means of suitable polishing tools.

CHAPTER X.

POLISHING.

The preparation of polishing tools has already been described. The polishing rouge which I use is of the quality which is used in large quantities commercially in polishing plate-glass. I prefer the powdered form always. This grade of rouge is not expensive (it costs about 30 cents per pound), but, like all rouge which I have seen, it contains hard, sharp particles which may cause scratches. It must therefore be thoroughly washed in the following manner:

In a clean, deep bowl *C* enough rouge is placed to fill it about one-third full; the bowl is then nearly filled with distilled water. The mass is very thoroughly stirred with a clean wooden paddle, and allowed to settle for about twenty minutes. The water above the rouge will now be perfectly clear; this water is siphoned off. With a clean spoon the light and fine rouge constituting the upper one-third of the precipitated mass is removed, and placed in a second clean bowl *D*. The rouge remaining in *C* may be again stirred up with an abundance of distilled water, and allowed to settle as before, the water siphoned off, and the upper one-fourth of the precipitated rouge removed and placed in *D*. The heavier rouge which remains in *C* is about half of the original quantity taken; this is usually reserved, and, after further washing, is used for polishing the backs of mirrors, and for similar work. Only the contents of the bowl *D* are used for fine work, and these are stirred up again and again with distilled water during the process of polishing, and only the fine, soft cream which remains on the top of the mass of rouge, when it settles each time, is used for polishing.

The thin cream of rouge and distilled water is applied to the glass by means of a wide brush consisting of a thin paddle of wood with clean cheese-cloth wrapped and tied about one end. Brushes of the usual kind should not be used.

By taking these precautions, and by the use of the wax surface on the rosin squares, scratches in polishing can be entirely avoided. It is true that the very light, fine rouge polishes more slowly than the heavier and coarser rouge, but an exquisitely fine polished surface is produced on the glass by its use. The wax surface also polishes more slowly than a bare rosin one, but it has the very great advantage that its action is more smooth and uniform than that of the rosin surface; the latter often tends to cling to the glass, and this unequally in different parts of the stroke.

The same question arises in regard to the size of polishing tools as in the case of grinding tools,—whether they shall be full-size or smaller. In the writer's opinion fine plane and spherical surfaces up to about 36 inches in diameter are best polished with full-size tools, which are moved by hand, by the optician and one or two assistants, upon the surface of the slowly rotating glass. The upper parts of the machine are, of course, removed during such polishing, which I shall call manual polishing.

A 24-inch polishing tool, prepared as already described, with its wooden basis $2\frac{3}{4}$ inches thick, weighs about 25 pounds; this is not heavy enough for the best action in polishing; so about 50 % additional weight is put on in the form of 12 lead blocks which are distributed uniformly and screwed to the back of the tool. This gives a weight of about $\frac{1}{12}$ pound for each square inch of area, which is found to work well for all large tools. For tools 18 inches or less in diameter somewhat greater pressure per square inch of area may be used. A 36-inch tool, with wooden basis $3\frac{3}{4}$ or 4 inches thick, weighs 75 or 80 pounds, and needs no additional weighting.

The work of polishing a 24-inch mirror with full-size tool will now be described. Six strong knobs of oak wood are screwed to the back of the wooden basis, each knob being at the center of weight of each sixty-degree sector of the tool. These knobs serve for pushing, pulling, and lifting.

The polishing tool, which, with the glass, should have cooled over night after the warm-pressing or rough-pressing previously described, is now to be cold-pressed. Cold-pressing is absolutely necessary in all fine work on large optical surfaces. In warm-pressing, both tool and glass are distorted by even slight warming, and when they become cool a perfect fit cannot be expected. The glass is carefully wiped with clean cheese-cloth, and an abundance of very thin mixture of rouge and water is spread upon it. The tool is now placed upon the glass and allowed to lie for several hours, being moved about slightly every ten minutes to redistribute the rouge and water, and to prevent the latter from drying around the edges. The pressing may be assisted at first by means of a 20- or 30-pound weight, the pressure of which *must* be distributed by some such means as three bars laid upon the six knobs, and a triangle, carrying the weight, laid upon these. The final cold-pressing must be done by the weight of the tool alone. The tool is taken off and examined occasionally; when it is sufficiently pressed the wax surface appears uniformly smooth and bright. So perfect a fit is secured in this way that there is no danger of injuring the form of the glass when polishing is begun. This applies to all stages of polishing and figuring. A fresh supply of rouge and water is now spread upon the glass.

The stroke of the 24-inch polishing tool is easily given by the optician and one assistant, who sit on opposite sides of the machine; the glass slowly rotates with the turntable, making about 2 revolutions per minute. The knobs on the back of the tool are held in the hands, and the stroke is given by alternately pushing and pulling; no vertical pressure whatever should be given by the hands. In addition, a considerable side-throw is always given, first to one side, then to

FIVE-FOOT MIRROR WITH FRONT AND BACK POLISHED APPROXIMATELY FLAT.
LOOKING THROUGH THE GLASS.

the other; this greatly assists in preventing the formation of zones of unequal curvature. Polishing may be begun with a stroke 6 inches in length, which of course causes the tool to overhang the glass 3 inches at the ends of the stroke; between 20 and 25 double strokes per minute are given. The side-throw used with this length of stroke is about 2 inches, *i. e.*, the tool is made to overhang the glass about 2 inches, first to the right, then to the left; the time occupied in passing from the extreme right to the extreme left is about what is required for 4 double strokes. This stroke and side-throw are continued while the glass makes exactly 2 revolutions; the tool does not rotate with the glass, of course, while the stroke is being given; the last stroke should end with the tool central upon the glass.

Tool and glass are now allowed to rotate together for $\frac{5}{6}$ of a complete revolution, and each optician then grasps the pair of knobs next to that which he held before, so that the stroke is now given along a diameter of the tool 60° from that last used; the length of stroke is now changed to 7 inches, and the side-throw to $2\frac{1}{2}$ inches, and polishing is again carried on during exactly 2 revolutions of the glass. Tool and glass are again allowed to rotate together for $\frac{5}{6}$ of a revolution, and polishing during 2 revolutions is now done with a stroke of 8 inches and side-throw of 3 inches. During the next periods of polishing, each of 2 revolutions of the glass, the stroke and side-throw are gradually shortened until a stroke of 4 inches or less is reached; then the length of stroke is increased again.

When polishing has been carried on during 6 or 8 periods of 2 revolutions each, it will be found necessary to supply more rouge. The only entirely satisfactory method of doing this, when a full-size polishing tool is used, is to remove the tool from the mirror, and quickly spread the thin cream of rouge and water upon the glass as uniformly as possible with the cheese-cloth brush. The removal of the tool is effected by the two opticians carefully sliding it off the mirror, and lifting at the same time. The tool should be allowed to remain off the glass for only as short a time as possible, so that the form of the latter shall not be altered as a result of a change of temperature of the surface, caused by evaporation. For this and other reasons, such as the prevention of dust, the air in the polishing room should be kept moist by keeping the floor well sprinkled.

When the tool is replaced on the mirror it is lifted by both opticians so that only a very small part of its weight remains on the glass, and is lightly moved about, for 30 seconds or more, to distribute the rouge and water thoroughly before polishing is continued. As before stated, the method just described is the only entirely satisfactory one, known to the writer, of supplying rouge during the polishing with a full-size tool. All methods of supplying rouge at the edge, or through holes in the tool, are inadmissible when the greatest refinement of figure is required.

It is in order that they may be easily handled in the manner described that full-size polishing tools should be made light. It would, of course, be possible to devise mechanism by which tools of any size and weight could be sufficiently counterpoised, could be moved about upon the glass, and could be removed from the latter for the purpose of supplying rouge. The simple and economical method which I have described, however, works well for mirrors up to 36 or 40 inches in

diameter. For larger mirrors it is more economical, in the opinion of the writer, to use half-size tools for obtaining a fully polished spherical surface, and the same and smaller tools for parabolizing. The method of using these will be described later.

In general, it is much easier to prevent the formation of zones, and to eliminate zones already present, with full-size polishing tools than with smaller ones. The method of manual polishing just described, in which the length of stroke and the amount of side-throw are very frequently changed, tends to give a spherical surface, except for a zone around the edge of the mirror one-half an inch or less in width; this part of the surface will be of too great focal length, *i. e.*, will turn down or back slightly, unless means are taken to prevent it. This tendency is most pronounced when a long stroke is used to excess, or when the rosin squares are too soft. It is entirely prevented by diminishing the area of the rosin squares around the edge of the tool, by trimming their edges to such a form as is shown in Fig. 4, page 28. The exact amount of trimming required depends upon the length of stroke, hardness of rosin, and temperature of polishing room, and therefore can be exactly determined only by experience.

A 24-inch mirror which has been properly fine-ground with emeries down to 2-hour or 4-hour washed, is readily brought to a perfect polish with a full-size tool in from 2 to 4 hours of actual polishing. If several broad zones of different focal lengths have resulted from the fine-grinding, as frequently happens, these zones can be gradually eliminated by a continuation of the use of the full-size polisher as above described.

Attention must be given to the rosin squares, which gradually press down so that their edges must be trimmed to keep the grooves of their original width and of uniform width. When the bare rosin begins to show at the corners or edges of the faces of the squares, which will occur after 6 or 8 hours' use of the tool, a new coat of wax must be applied, and the tool must again be thoroughly cold-pressed. It must not be supposed, however, that cold-pressing is necessary only at such times; in all fine work this pressing must be done whenever the tool has remained off the glass for more than a few minutes; after hanging face down during the night the tool is always cold-pressed for about 2 hours before polishing is begun in the morning.

Polishing with half-size or smaller tools is best done with the machine, instead of by manual work. These tools do not have to be removed from the glass in order to renew the supply of rouge; they are therefore connected to the machine and used very much as half-size grinding tools are used; in my work they are made of such weight that they need not be counterpoised. Very large or unusually heavy polishing tools of this kind can, of course, be easily counterpoised when desired.

Great experience, constant attention to very frequent changing of the position of the tool by means of the transverse slide, and frequent testing of the form of the mirror surface are necessary in polishing with half-size or smaller tools, in order to preserve the uniform curvature of the surface. This is greatly facilitated by trimming the rosin squares at and near the edges of the tool, as in the case of full-size

tools, but to a greater extent; the effect of the action of the edges of the tool is thus softened or blended.

When a half-size or smaller tool has just been coated with wax, or is known to be far from the exact form desired, it is first cold-pressed in the usual way on the center of the glass. But the final cold-pressing of such tools should be done as follows: The entire surface of the glass is painted with rouge and water, and the machine is set to give a "normal" stroke, *i. e.*, one by which the tool is made to cover the entire surface of the mirror as uniformly as possible (without an excess of action on any zone) as the glass revolves; the machine is run extremely slowly, and the setting of the transverse slide is changed often; after pressing the tool for an hour or two in this way, polishing or figuring is to be begun.

CHAPTER XI.

TESTING AND FIGURING SPHERICAL MIRRORS.

Before describing the work of figuring concave mirrors, which is done with polishing tools, it will be necessary to consider methods of testing. The principles involved in testing concave mirrors at their center of curvature by Foucault's method have been thoroughly explained and illustrated by Draper on pages 13–19 of his book, and by Dr. Common in his book *On the Construction of a Five-Foot Equatorial Reflecting Telescope.* Foucault's original paper on this subject may be found in Vol. V of the *Annals of the Paris Observatory.*

All mirrors, when being tested, are placed on edge, so that the axis of figure is nearly horizontal, large mirrors being suspended in a wide, flexible steel band, lined with soft paper or Brussels carpet; for glass mirrors larger than 30 inches in diameter it is very desirable to have the grinding and polishing machine so constructed that the glass can be turned down on edge for testing, in the manner shown on Plate II, without removing it from the machine. A 30-inch glass mirror 4 inches thick weighs about 260 pounds; mirrors larger than this are difficult to handle without suitable mechanism.

A small, brilliant source of light, or "artificial star" may be produced by placing in front of the flame of an oil lamp a thin metal plate in which a very small pinhole has been bored. If the illuminated pinhole be placed about an inch to one side of the principal axis of the mirror, and at a distance from the mirror equal to its radius of curvature, a reflected image of the pinhole will be formed on the other side of the axis, and at the same distance from it and from the mirror as the corresponding distances of the pinhole itself. If the surface of the mirror is perfectly spherical, and if there are no atmospheric disturbances in the course of the rays, the reflected image, when examined with an eyepiece, will be found to be a perfect reproduction of the pinhole, with the addition of one or more diffraction rings around it, minute details of the edge of the pinhole appearing as exquisitely sharp and distinct as when the pinhole itself is examined with an eyepiece. If the

eyepiece be moved outside and inside of the focus, the expanded disk in both cases appears perfectly round. Nothing can be more impressive than to see such a reflected image produced by a fine spherical mirror having a radius of curvature of 100 feet or more. Several such mirrors of 2 feet aperture have recently been finished here.

The use of an eyepiece is interesting for such experiments as that just described, and is important as a check upon the test with an opaque screen. The latter test, however, which I shall call the knife-edge test, is used almost exclusively for mirrors of all forms; it is far more serviceable than the eyepiece test in determining the nature and position of zonal irregularities, and is far more accurate in determining the radius of curvature either of a mirror as a whole, or of any zones of its surface.

If the eye be placed just behind the reflected image of the illuminated pinhole, so that the entire reflected cone of light enters the pupil, the polished, unsilvered mirror surface is seen as a brilliant disk of light. Let an opaque screen or knife-edge be placed in the same plane through the axis as the pinhole, and be moved across the reflected cone *from the left*, and just in front of the eye; if a dark shadow is seen to advance across the mirror from the left, the pinhole and knife-edge are inside of the best focus, and must be moved together away from the mirror; if, however, with the knife-edge still moved across from the left, the shadow advances across the mirror from the right, pinhole and knife-edge are outside of the focus and must be moved toward the mirror. By repeated trials a position is found from which the shadow does not appear to advance from either side, but the mirror surface darkens more or less uniformly all over: this is the position or plane of the best focus, and it is with this position of the knife-edge that irregularities of the surface, if any exist, are seen in most highly exaggerated relief; with this position of the knife-edge, the mirror, if perfectly spherical, is seen to darken with absolute uniformity all over as the screen is moved across the focus, and the impression of a perfectly plane surface is given to the eye.

If, however, the mirror is not perfectly spherical, but contains several zones of slightly different radii of curvature, a very common case, these zones will appear as protuberant or depressed rings on an otherwise plane surface. The reason for this is evident; the light from some parts of such zones is cut off by the knife-edge *before*, from other parts *after*, the illumination from the general surface is cut off; the surface is therefore seen in light and shade, *i. e.*, in enormously exaggerated relief. The mirror must be regarded as being illuminated by light shining very obliquely along the surface from the side opposite that from which the knife-edge advances across the focus. The interpretation of lights and shades becomes easy after a little experience; not only is the character of a zone—whether it is an elevation or depression—readily seen, but its diameter and its width are readily determined.

If the disk of glass is of sufficient thickness and of proper quality, and if attention has been given to the uniform rotation of the turntable and to the protection of the glass from abnormal conditions of temperature during grinding and

polishing, all irregularities of figure which occur are perfect zones or rings concentric with the edge of the glass; that is, the surface is always a perfect surface of revolution. If, however, these precautions have not been taken, or if the glass has been improperly supported during grinding and polishing, or if it has been cut out of thick *rolled* plate-glass, so that it is weak in the direction of one diameter, an astigmatic mirror may be produced, in which the radius of curvature is slightly different along two diameters at right angles to each other.

Astigmatism is easily recognized with either the knife-edge or the eyepiece test. Let the plane of the apparent focus be determined with the knife-edge advancing from the left, then from above, then from the right, then from a number of directions between these three; if astigmatism exists the planes of the various foci thus found will not coincide; and the directions of greatest and least curvature of the surface are readily determined. When the eyepiece test is used, an astigmatic mirror does not give a sharp image even at the best focus; if the eyepiece be moved outside and inside of this focus the expanded disk becomes elongated, and is not uniformly illuminated; the direction of elongation outside is at right angles to that inside, and the distribution of light in the expanded disk is entirely different outside and inside of the focus.

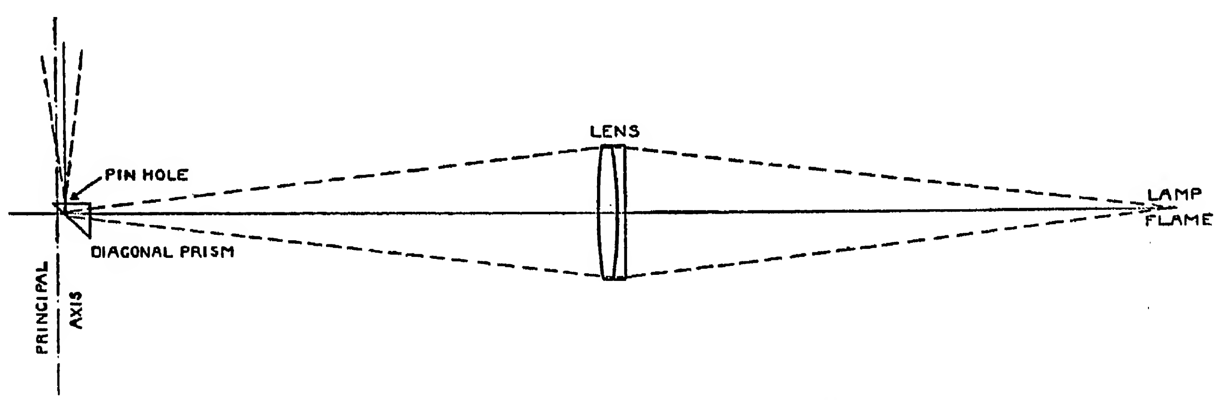


FIG. 1.

ARRANGEMENT BY WHICH ARTIFICIAL STAR IS USED VERY CLOSE TO OPTICAL AXIS.

The general character of the tests having now been described, let us consider some important matters of detail which are necessary for the greatest refinement in testing all forms of mirrors.

By the use of a small lens and a diagonal prism, in the manner shown in Fig. 1, the lamp can be kept well out of the way, and the illuminated pinhole and its reflected image brought very near to the axis of figure of the mirror. This is of much importance in testing mirrors of short focus or of great angular aperture, as the danger of errors in testing due to working considerably out of the axis of figure is avoided. As may be seen in the figure the pinhole is now placed at the surface of the diagonal prism nearest to the mirror being tested. The arrangement should be such that the cone of rays proceeding from the lens is considerably larger than is needed to fill the concave mirror.

When being figured, mirrors are usually tested while unsilvered, since very frequent tests are desirable. While the amount of light reflected from the polished

unsilvered surface is surprisingly great, a much more brilliant "artificial star" than that given by the oil lamp is required for the greatest refinement and accuracy with the knife-edge test, especially in the cases of plane, paraboloidal, and hyperboloidal mirrors, in which there are two reflections from the unsilvered surface. It might be supposed that a larger pinhole could be used, and thus a more brilliant illumination of the mirror surface secured; but a large pinhole allows an apparent diffusion of light over the mirror surface, which obliterates all the more delicate contrasts of illumination due to minute irregularities of surface. With feeble illumination of the surface the eye is entirely unable to detect slight contrasts, which with brilliant illumination become strong and unmistakable. When the knife-edge test is used with an extremely small pinhole of between $\frac{1}{250}$ and $\frac{1}{500}$ inch in diameter, illuminated by acetylene or (what is much better) oxy-hydrogen or electric-arc light, minute zonal irregularities are strongly and brilliantly shown, which are entirely invisible with large pinhole or insufficient illumination. With the arrangement of lens and diagonal prism (Fig. 1) either of the sources of light named can be used without difficulty; disturbances of the air from their heat should be prevented by placing the light behind a partition with a window of thin plate glass.

With the best conditions of apparatus just described, the degree of accuracy to be attained with the knife-edge test is surprising. With a mirror of 2 feet aperture and 50 feet radius of curvature, the plane of the center of curvature can be easily located to within $\frac{1}{100}$ inch, and with care to within half of that amount. With the dimensions given, a change of $\frac{1}{100}$ inch in the radius of curvature corresponds to a change of $\frac{1}{500,000}$ inch in the depth of the curve of the mirror surface. There can be no doubt that zonal irregularities of surface of half of this amount are readily recognized.

We are now ready to consider the finishing of a spherical mirror. As before stated, a continuation of the use of the full-size polishing tool tends toward the gradual elimination of zonal irregularities. This work is often slow and laborious, however, for when the mirror becomes nearly finished, so that any zones, when seen with the knife-edge test, appear as extremely slight elevations or depressions, the improvement becomes exceedingly slow. The work may be facilitated by the local use of very small polishing tools upon protuberant zones. These tools are usually from 2 to 4 inches in diameter, and consist of squares of rosin upon a basis of brass; their faces are waxed and cold-pressed, and the squares around their edges are trimmed in order to soften or blend the action of the edges; small local tools with their surfaces trimmed as shown in Fig. 13 (in which the shaded parts represent the rosin) are excellent for the purpose. These local tools are used as follows: the positions and width of any protuberant zones are carefully determined by the knife-edge test, and the glass is replaced on the rotating turntable; stationary pointers are clamped to the machine, and overhang the glass so as to indicate the exact positions of the zones; the surface is painted all over with rouge and water, and the optician works the small tools on the high zones by hand; the rubbing is done on each zone during several revolutions of the glass, the length and direc-

tion of the stroke being changed after each complete revolution. Great care and judgment must be used in this work, and the surface must be tested very often, otherwise a wide zone will usually give place to several narrow ones. After the protuberant zones have been softened down in this way the full-size polisher is again used for finishing the surface.

A large and perfect spherical mirror is an indispensable part of the equipment of an optical laboratory, as it affords what is in my opinion the most satisfactory means of testing large plane mirrors. On account of the ease of rigorously testing a concave spherical surface, this is the form which should be first attempted by beginners in optical work.

CHAPTER XII.

GRINDING, FIGURING, AND TESTING PLANE MIRRORS.

THE making of large plane mirrors of fine figure is usually regarded as much more difficult than that of large concave mirrors. The difficulty has been, in the past, largely one of testing. With a satisfactory method of testing the large plane surface *as a whole*, in a rigorous and direct manner, the problem is greatly simplified. So far as the writer is aware, no such test has hitherto been fully developed. In *Monthly Notices*, Vol. 48, p. 105, Mr. Common suggests, very briefly, the testing of plane mirrors in combination with a finished spherical mirror, and gives a diagram in illustration; but no details in regard to the method are given. This method has been developed and used for many years by the writer in testing plane mirrors up to 30 inches in diameter. When this test is used, the difficulty of making a 24-inch plane mirror which shall not deviate from perfect flatness by an amount greater than $\frac{1}{500,000}$ inch is neither greater nor less than that of making a good spherical mirror of 2 feet aperture and 50 feet radius of curvature, when it is required that the radius of curvature shall not differ from 50 feet by a quantity greater than $\frac{1}{100}$ inch.

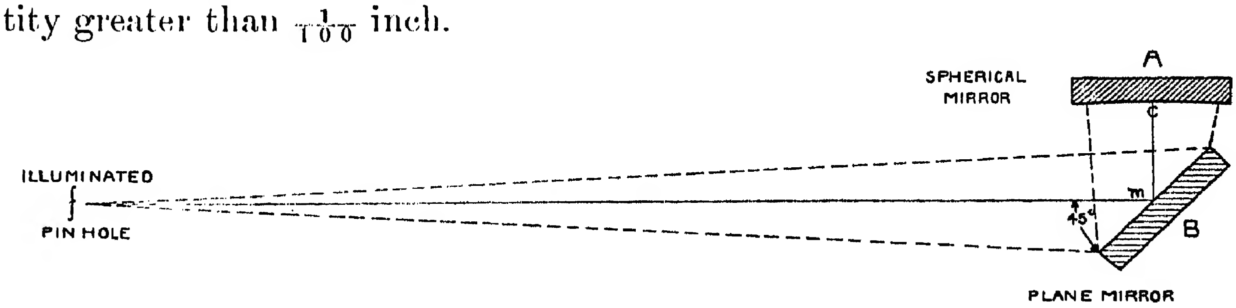


FIG. 2. DIAGRAM ILLUSTRATING TESTING OF A PLANE MIRROR.

A spherical mirror A (Fig. 2), which should not be smaller in diameter than the plane mirror B to be tested, is figured with the utmost accuracy, special care being taken that no astigmatism, however slight, exists in it. The mirror A is silvered; B is polished and unsilvered. The mirrors may be set up as shown *in plan* in Fig. 2, the distance $cm + mf$ being equal to the rádius of curvature of A; both mirrors hang on edge in steel bands as already described. The light proceeding

from the illuminated pinhole strikes *B*, is reflected to *A*, thence back to *B*, thence to a focus close beside the illuminated pinhole.

When using the knife-edge test the optician sees the mirror *B* brilliantly illuminated, and in elliptical outline, the horizontal diameter appearing foreshortened by an amount depending upon the angle at which the mirror is viewed. With the knife-edge test the surface of *B* is seen in relief, as a whole ; any zonal errors appear enormously exaggerated, and their character and position are readily determined, just as when a spherical mirror is tested at its center of curvature ; these zonal errors, of course, appear elliptical, on account of their foreshortening ; their effect is doubled in intensity on account of the two reflections from *B* (assuming that the illumination is as brilliant as the eye requires).

The test, as already described, is all that is necessary for the detection and location of zonal errors. But something more is necessary in order to detect general curvature, *i. e.*, convexity or concavity, in *B*. Let us assume that the mirror, when fine-ground and polished, is so nearly flat that no curvature can be detected with a Brown and Sharpe steel straight-edge of the finest quality ; and for convenience in description let us also assume that the surface is free from zonal errors. Let the knife-edge be moved across the reflected cone from the left ; a focal point is found at which the right and left sides of the mirror darken simultaneously ; this focal point we will call f_1. Now let the knife-edge be moved across the cone from above, instead of from the left ; a focal point will be found at which the upper and lower parts of the mirror darken simultaneously ; this focal point we will call f_2. It is only when the mirror *B* is a perfect plane that f_1 and f_2 coincide with each other and with the point f (see figure). If *B* is slightly convex, f_1 and f_2 are outside of f (*i. e.*, farther from the mirror than f) and f_1 is outside of f_2. If *B* is slightly concave both f_1 and f_2 are inside of f, and f_1 is inside of f_2. In practice, the exact position of f is not found (except incidentally when the plane mirror is finished), for this would involve the very accurate measurement of the large distance $cm + mf$. The determination of the positions of f_1 and f_2 with reference to each other is all that is needed.

That f_1 and f_2 do not coincide when *B* is convex or concave is due to the fact that the curvation of *B* is apparently increased or exaggerated in the direction of the horizontal diameter of the mirror, on account of its foreshortening in this direction, as seen from f; while the curvature in the direction of its vertical diameter is not thus exaggerated. The effect is precisely as if the spherical mirror *A* were astigmatic, the parts of the surface adjacent to the horizontal diameter having a different radius of curvature from those adjacent to the vertical diameter. This effect is so marked that an extremely small deviation of *B* from a true plane can be detected. For example, if *A* and *B* are each two feet in diameter, the radius of curvature of *A* being fifty feet as before, and if the angle which the line fm subtends with the surface of *B* is 45°, a deviation from a true plane of $\frac{1}{350,000}$ inch in the surface of *B* is readily detected. If the angle of the mirror *B* be changed to 30°, as shown in Fig. 3, the accuracy of the test for general curvature is about doubled ; the latter position, however, is not usually so convenient for determining the positions of zonal

errors; for the greatest refinement, therefore, the stand on which A and B are supported is so designed that the positions of the mirrors can be quickly changed so as to give the greatest accuracy in each part of the test.

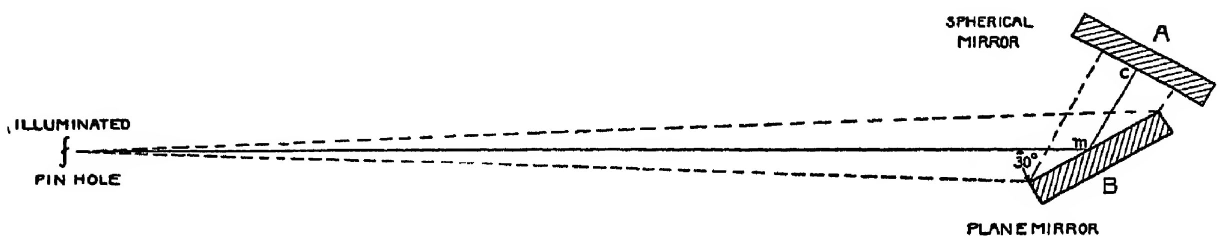


FIG. 3. DIAGRAM ILLUSTRATING TESTING OF A PLANE MIRROR.

The use of an eyepiece in this test is important because it shows how fatal to good definition is even a very slight convexity or concavity of a plane mirror when used in oblique positions. If f_1 and f_2 coincide as closely as can be detected with the knife-edge test (B being free from zonal irregularities also) the reflected image of the pinhole, as seen in an eyepiece at f, is as exquisitely sharp and perfect as if it were formed by the spherical mirror A alone. But if B is slightly convex or concave the appearance of the eyepiece image is similar to that which has already been described in connection with astigmatic concave mirrors; the image is not sharp even at the best focus; if B is convex, the image becomes elongated in a vertical direction outside, and in a horizontal direction inside, of the best focus; if B is concave the directions of elongation are the reverse of these.

The preparation of grinding tools for plane mirrors is similar to that of tools for concave mirrors. Three full-size, flat iron tools are usually made, however, all of which are grooved. These are ground together with carborundum of finer and finer grades, until all appear flat when tested with a carefully kept Brown and Sharpe steel straight-edge of best quality.

The plane mirror is fine-ground in the manner described for concave mirrors. It is of course a rare occurrence to find a large plane mirror nearly optically flat when it is first tested after grinding and polishing. My large mirrors almost invariably come out slightly convex when first polished; this may be due in part to the fact that the flat grinding tool becomes very slightly concave during the fine-grinding of the glass, from being worked on top (see page 7). Slight convexity of the mirror at this stage of the work is much better than slight concavity, for it is much better and easier to remove a high center than a high edge, during the process of figuring with polishing tools.

Manual polishing with full-size tools should be employed when the mirror is not too large to allow this. The polishing is begun with the *normal* tool shown in Fig. 4, in which the grooves are of uniform width throughout. After an hour's polishing the mirror is tested; if it is found to be convex, polishing is continued with the *concaving* tool shown in Fig. 5, in which all of the grooves are gradually widened toward the edges of the tool, so that there is a progressive decrease of action toward the edges of the glass; the amount of this widening must be

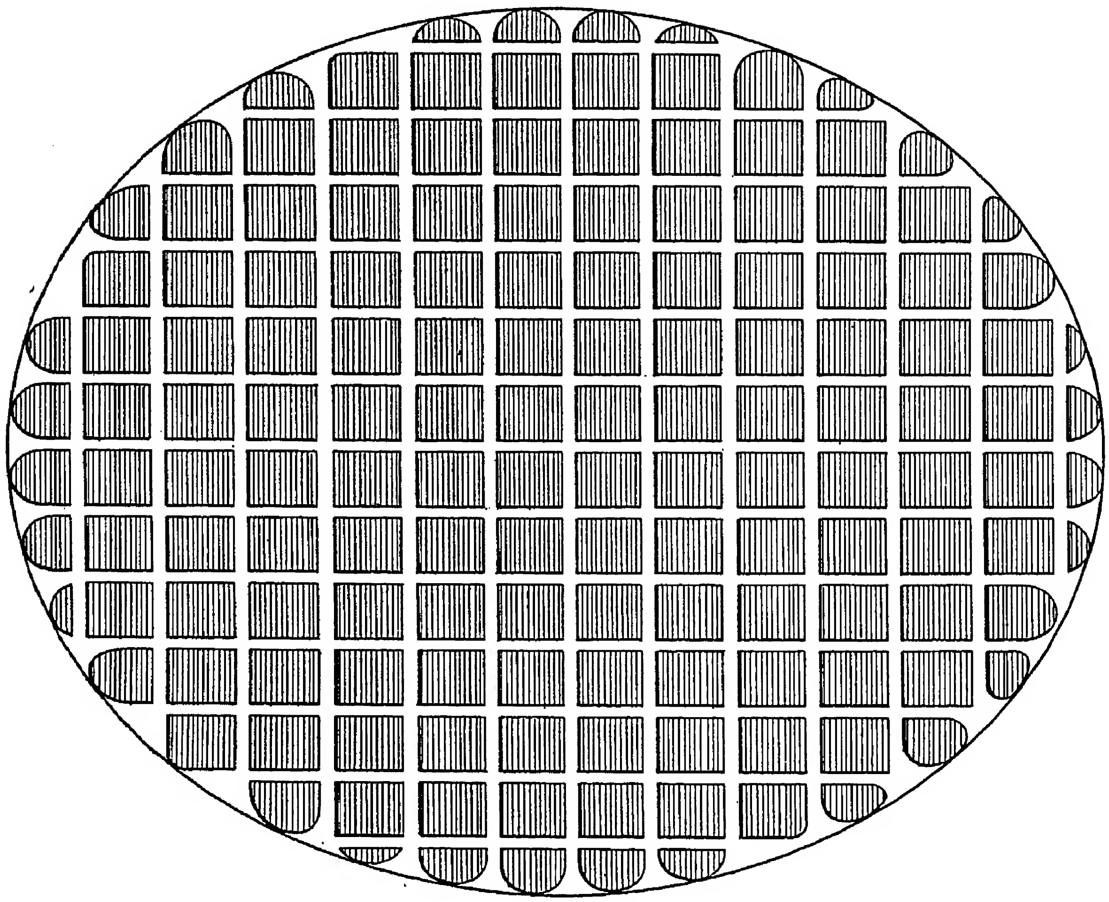


FIG. 4. NORMAL POLISHING TOOL.

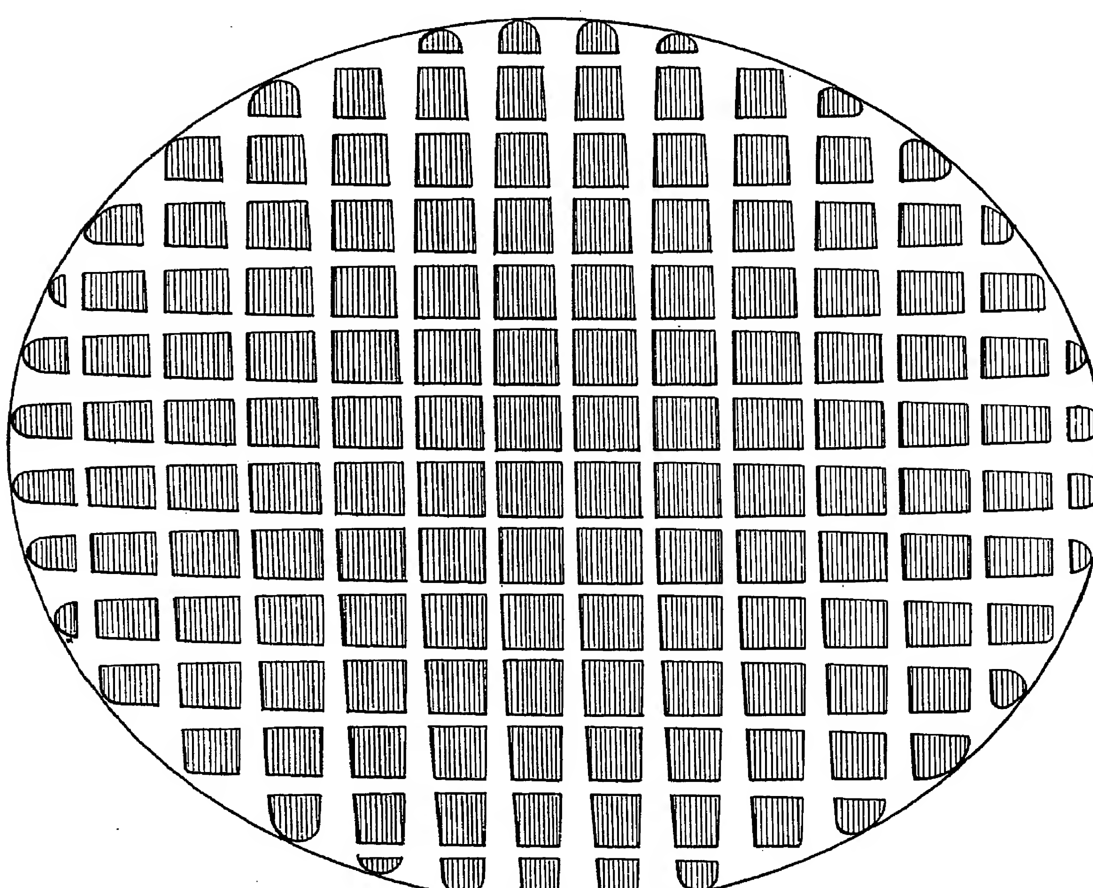


FIG. 5. CONCAVING POLISHING TOOL FOR FIGURING PLANE MIRROR.

determined by experiment; it should be such that the convexity of the mirror is slowly and uniformly decreased.

If the mirror, when first tested, is found to be concave, the *convexing* tool shown in Fig. 6 is used to continue the polishing.

The concaving and convexing tools often tend to introduce broad slight zonal errors; hence recourse must be had repeatedly to the normal tool. When all trace of *general curvature* has disappeared, any remaining zonal errors are eliminated by the use of the normal tool, and, if necessary, of the small local or figuring tools, (see page 24).

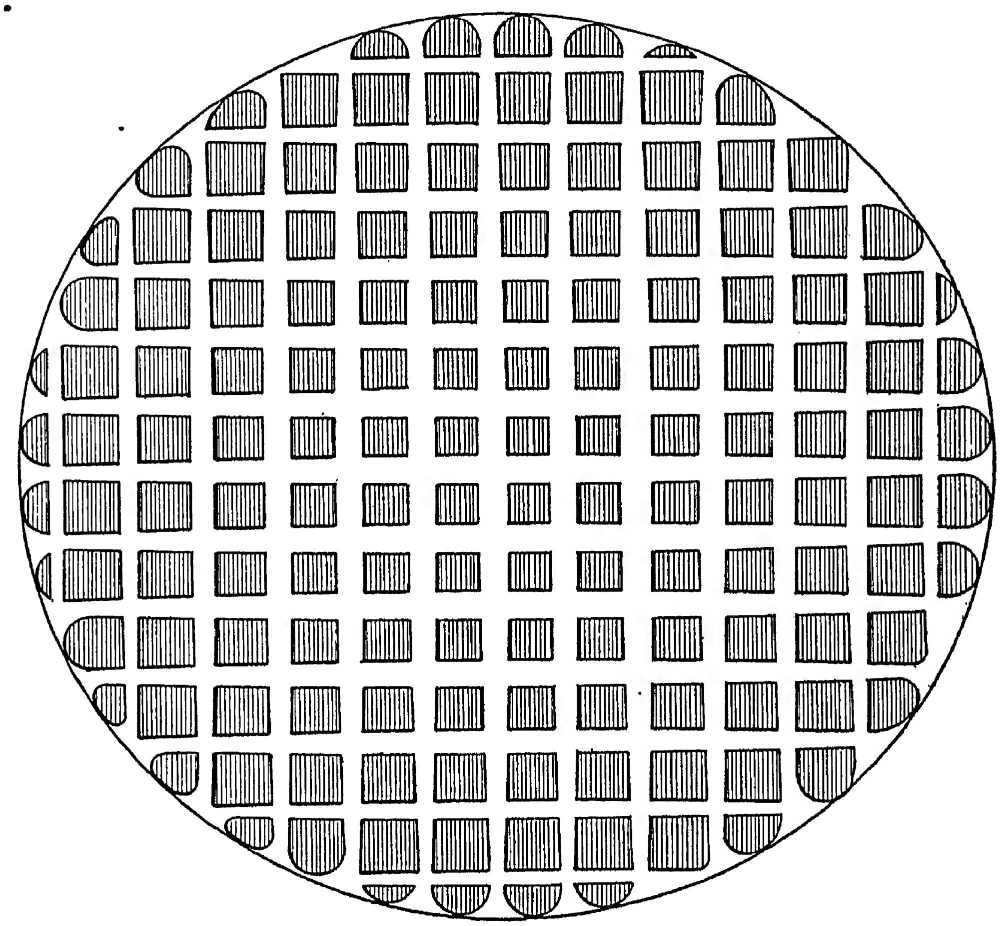


FIG. 6. CONVEXING POLISHING TOOL FOR FIGURING PLANE MIRROR.

If a finished plane mirror is available which is not smaller than the one being figured, the work is very greatly facilitated by continually cold-pressing the polishing tools on the finished mirror; every precaution must be taken, however, to prevent injury to the figure of the finished mirror by such cold-pressing.

In some of the writer's early work, in which the thickness of mirrors was made only one-twelfth of their diameter, it was found that a *normal* polishing tool, as described above, tended to change the mirror very gradually toward a concave. This was undoubtedly due to the fact that the friction of polishing warmed the surface very slightly, thus expanding it and making it convex with reference to the polishing tool; the tool did not follow this change of form readily, hence the central parts of the glass were acted upon in excess. Furthermore, such thin mirrors, when unsilvered, were so sensitive to slight changes of temperature that the presence of the

optician's body for a period of two or three minutes, at a distance of three feet from a mirror which was set up for testing, would throw a previously plane mirror convex by an amount many times greater than the smallest amount which can be detected by the knife-edge test. When the thickness of mirrors is made equal to about one-seventh of their diameter, their sensitiveness to all such temperature effects is very greatly decreased. Furthermore, in the case of silvered glass mirrors which are used for solar work, the writer has found that thick mirrors suffer very much less change of figure from exposure to the sun's heat than thin mirrors do. Silvering affords a great protection from changes of temperature, since the silver film furnishes an almost totally reflecting surface for heat radiations.

CHAPTER XIII.

TESTING AND FIGURING PARABOLOIDAL MIRRORS.

THE work of changing a spherical mirror to a paraboloidal one is accomplished entirely by the use of polishing tools, by shortening the radii of curvature of the inner zones, instead of by increasing or lengthening those of the outer zones. The methods of effecting this change of curvature will be described after the methods of testing a paraboloid have been discussed.

Such testing can be done at the center of curvature, by determining there the foci or the radii of curvature of successive zones of the mirror; it may be done at the *focus* of the paraboloid, by the aid of a finished plane mirror which should be at least as large as the paraboloidal one; and it may be done directly on a star. The first two methods named have the very great advantage that they may be conducted without interruption, under the practically perfect atmospheric and temperature conditions of the optical laboratory.

Testing a Paraboloid at the Center of Curvature. A knowledge of the properties of the parabola enables the optician to compute the positions of the centers of curvature of successive, definite, narrow zones of the mirror, and the surface must be so figured that the radius of curvature of each zone agrees with the computed value. In testing, each zone in succession is exposed by means of a suitable diaphragm, all of the rest of the surface being covered. In practice, two entirely different formulæ may be used, depending upon the position of the illuminated pinhole.

Let F be the focal length of a finished paraboloidal mirror, and R the semi-diameter of any extremely narrow zone or ring of its surface, concentric with the vertex or center of the mirror; the normals to this zone cross the axis at a point whose distance from the vertex is $2\,F+\frac{R^2}{4\,F}$; hence, if the illuminated pinhole be placed very close to the axis, and at a distance of $2\,F+\frac{R^2}{4\,F}$ from the vertex, the rays of light reflected from the narrow zone will form a focus or image in the same

plane (at right angles to the axis) in which the pinhole itself lies. This is the simplest formula which can be used, but it is not the most useful in practice.

In testing paraboloids at the center of curvature the writer has always used the following method and formula: The illuminated pinhole remains fixed at the center of curvature of the central parts of the mirror, *i. e.*, at a distance 2 F from the vertex, where F is the focal length. The intervals, measured along the axis, between the reflected foci of the various zones, are now twice as great as those given by the method described in the preceding paragraph; consequently these foci can now be determined with twice the accuracy which can be attained by that method. Only the rays reflected from the parts of the paraboloid very near to the vertex are now brought to a focus in the plane of the pinhole. If the paraboloidal figure is perfect, the rays reflected from any very narrow zone whose semi-diameter is R are now brought to a focus at a distance $\frac{R^2}{2\,F} + \frac{R^4}{16\,F^3}$ back of the plane the pinhole, *i. e.*, at a distance $2\,F + \frac{R^2}{2\,F} + \frac{R^4}{16\,F^3}$ from the vertex of the paraboloid. The quantity $\frac{R^4}{16\,F^3}$ is so small in the case of mirrors of moderate size and of ordinary ratios of aperture to focal length that it can be neglected; even in testing the outermost zones of the 5-foot mirror of 25 feet focal length, this quantity is less than 0.002 inch, while the quantity $\frac{R^2}{2\,F}$ amounts to $1\frac{1}{2}$ inches.

Now let us consider what is the best method of determining the planes of the reflected foci. Draper, Common, and other workers used an eyepiece for this purpose; this serves well for mirrors of moderate angular aperture, but for mirrors in which the ratio of aperture to focal length is as great as 1 to 5 or 1 to 6 this method presents serious difficulties; if narrow zones are used the image in the eyepiece is blurred and indistinct on account of the diffraction effect produced by the edges of the zonal openings in the diaphragm, while if wide zones are used the difference of focus of the inner and outer parts of a zone is so great that the image shows evidence of marked aberration; with neither narrow nor wide zones can the position of the focus be determined with very great accuracy.

In *Publications of the A. S. P.*, vol. xiv., No. 87, Hussey gives a formula for the position of the "circle of least confusion" when a zone of *given width* is used; if Hussey's formula were employed and the pinhole were made very small and round, with smooth edges, it is probable that much greater accuracy could be attained than by the use of an eyepiece in the ordinary way.

The method of locating the reflected foci which is used by the writer is as follows; it is capable of surprising accuracy when the optician has become experienced in its use. The reflected focus of a zone is found with the knife-edge, precisely as the focus of a spherical mirror is found. The knife-edge is moved across the reflected cone from the left; if the left side of the zone is seen to darken first, the knife-edge is inside of the focus; if the right side darkens first, the knife-edge is outside of the focus; when the right and left sides of the zone darken simul-

taneously, the knife-edge is at the focus of the zone. One advantage of this method is that it is independent of changes of focus of the eye itself; but the great advantage is that very narrow zones or arcs can be used. Diaphragms with zonal openings $\frac{1}{4}$ of an inch wide serve admirably for mirrors of 10 or 15 feet focal length; indeed the width of the zones which are actually used is considerably less than this; for, on account of diffraction, the edges of the openings in the diaphragms always appear as brilliant lines, even while the illumination near the center of the openings is being cut off by the knife-edge; it is therefore only the illumination near the center that is used in making the comparison.

The diaphragms which I use in this method of testing do not expose entire zones, but only pairs of arcs on the right and left sides of the mirror. Fig. 7 shows the diaphragm which was used in testing in this way the mirror of the two-foot reflector of the Yerkes Observatory. The arcs are cut in a long and narrow strip of thin metal; this is attached to the inner edges of two wooden strips, *a;* these

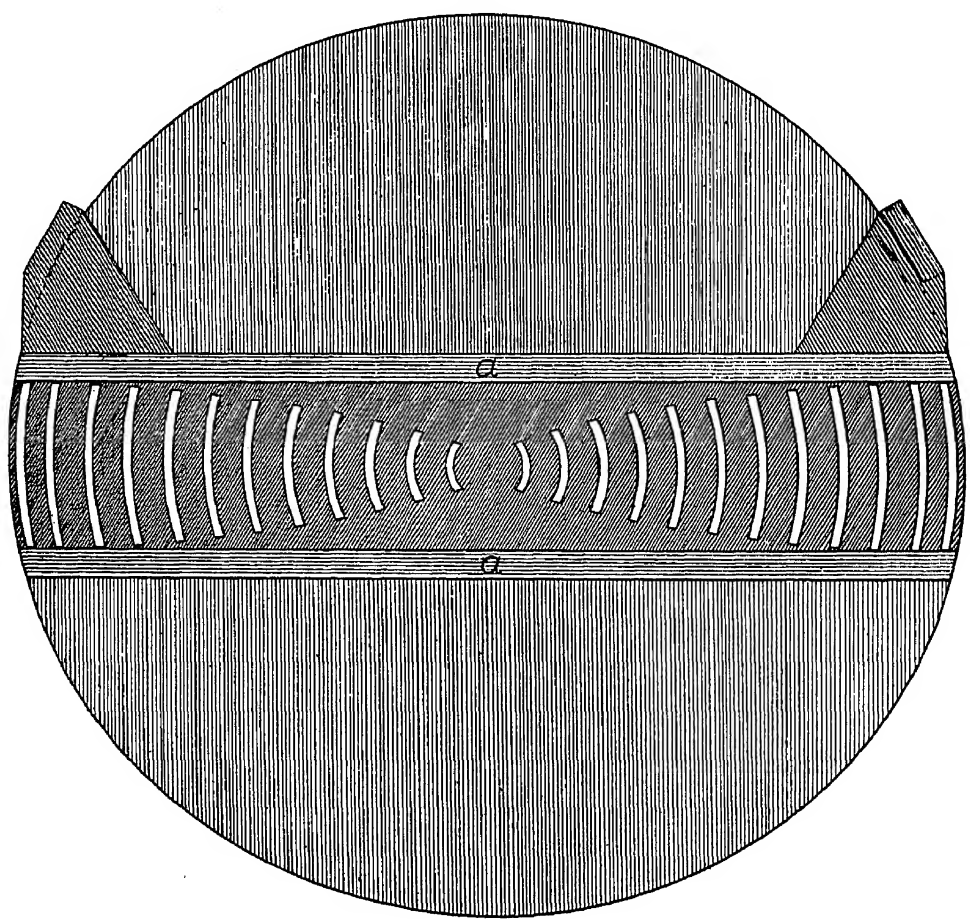


FIG. 7. DIAPHRAGM USED IN TESTING A PARABOLOIDAL MIRROR AT ITS CENTER OF CURVATURE.

edges are curved so that all parts of the thin metal diaphragm are nearly in contact with the curved surface of the mirror. The edges of the openings are bevelled so as to be extremely thin, and are finished dead-black. Twelve pairs of arcs were used, with mean radii of 1, 2, 3, . . . 10, 11, and $11\frac{7}{8}$ inches. The openings of these arcs are $\frac{1}{4}$ inch in width. The foci of the successive zones (except those near the center) can be readily determined by this means to within

$\frac{1}{500}$ inch along the axis, for a mirror of two feet aperture and of ten or fifteen feet focal length.

Care must be taken when testing in this way that the entire mirror surface is *uniformly illuminated* by the cone of light proceeding from the illuminated pinhole; this condition, once secured, is easily maintained, since the illuminated pinhole remains immovable.

I have described at considerable length the methods of testing paraboloids at the center of curvature, because of the importance of the subject, and because this will probably continue to be a favorite method, especially among amateurs. But when testing is done at the center of curvature, even with the extremely accurate method just described, the making of a large paraboloidal mirror of great angular aperture and really fine figure is an exceedingly difficult task. This is due in part to the necessity of very frequent tests, in each of which the foci of a large number of zones must be determined; it is due far more to the uncertainty in determining the exact nature of errors of surface (considering the surface as a whole) corresponding to focal readings which do not agree with the computed values. In the case of mirrors of small or moderate angular aperture, much important information can be gained by viewing the surface as a whole, from the (mean) center of curvature, by means of the knife-edge test; a finished paraboloid, when thus seen, appears to stand out in relief, in strong light and shade, as a surface of revolution whose sec-

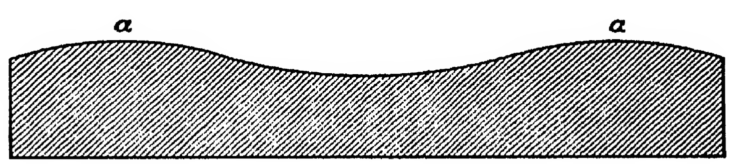


FIG. 8.

tion is that shown in Fig. 8; knife-edge and pinhole are both at the center of curvature of the zone *a*; the apparent curve of the surface should be a smooth one. But in the case of a mirror of large angular aperture the change of curvature is so rapid that only a narrow zone can be seen well at one time, *i. e.*, with a given focal setting of the knife-edge.

Testing a Paraboloid at its Focus. This method was briefly described by the writer in the *Astrophysical Journal*, November, 1901. It is incomparably more simple, direct, and rigorous than the test at the center of curvature. A well-figured plane mirror, which should not be smaller than the paraboloidal one, is necessary in order that the testing may be done in the optical laboratory. In practice a small diagonal plane mirror is also used, to avoid the necessity of a central hole through the large plane mirror. Both of the plane mirrors are silvered. The arrangement of mirrors is shown in Fig. 9. The diagonal prism is placed at f, with the illuminated pinhole very near the axis; pinhole and knife-edge are in the same plane, at a distance from the vertex equal to $cm + mf$, which is equal to the focal length of the mirror. The paraboloid is now tested as a whole, without the use of zones, precisely as a spherical mirror is tested at its center of curvature.

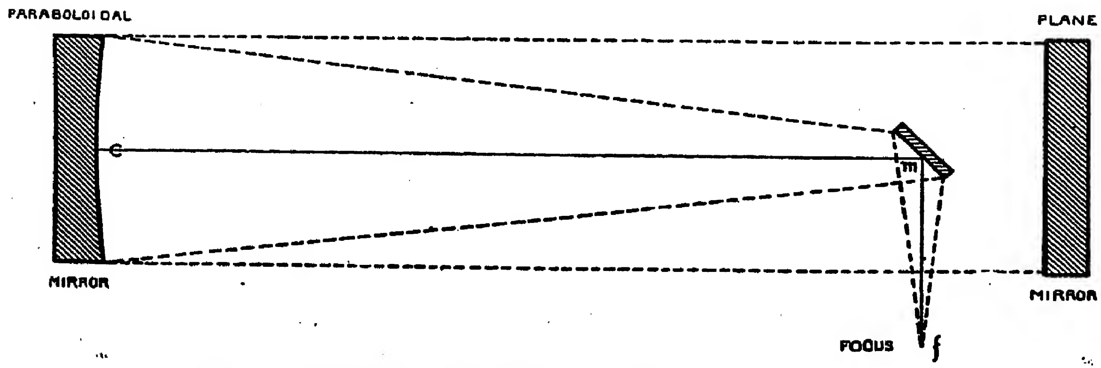


FIG. 9. TESTING A PARABOLOIDAL MIRROR AT ITS FOCUS.

If F be the desired focal length of the paraboloidal mirror whose semi-diameter is R, then the spherical surface which is fine-ground and fully polished preparatory to parabolizing should have a radius of curvature of $2F + \frac{R^2}{4F}$. This is because parabolizing is done by shortening the radii of curvature of all the inner zones of a mirror, leaving the outermost zone unchanged, as shown in Fig. 10; this is a far easier and better method in practice than to leave the central parts of the mirror

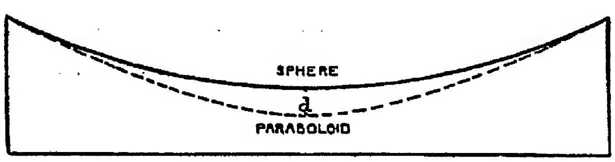


FIG. 10.

FIG. 11.

unchanged, and to lengthen the radii of curvature of all of the outer zones, as shown in Fig. 11:

Let us now suppose that the concave mirror shown in Fig. 9 is a *spherical* one with radius of curvature $2F + \frac{R^2}{4F}$, where R is the semi-diameter, and F is the distance $cm + mf$, from the center of the mirror surface to the plane of the pin-hole and knife-edge. If the spherical surface be now viewed from the point f with the knife-edge test, it will appear to stand out in relief, in strong light and shade,

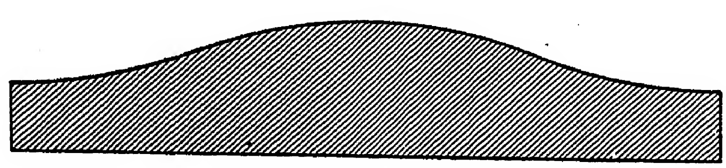


FIG. 12.

as a surface of revolution whose section is that shown in Fig. 12, the height of the protuberant center depending upon the angular aperture of the mirror. The reason for this appearance is readily seen by reference to Fig. 10. To change the spherical surface to a paraboloid, the protuberant center must be removed by the use of suitable polishing tools, until the surface, as seen with the knife-edge test from the point f, appears perfectly flat, *i. e.*, the illuminated surface darkens with perfect

uniformity all over. As the paraboloidal surface nears completion, an elevated or depressed center, a "turned up" or "turned down" edge, or protuberant or depressed zones, can be seen and their character and exact position determined, with precisely the same ease and certainty with which similar irregularities are seen when a spherical mirror is examined at its center of curvation with the knife-edge test.

It should be noticed that even when the pinhole and reflected image are very near each other, as they should be, yet both may be far out of the axis of the paraboloid, if the mirrors are not properly adjusted or collimated; when this is the case the mirror surface, when seen with the knife-edge test, does not appear as a surface of revolution, and cannot be properly tested. The mirrors may be collimated by the following method, thus insuring that the pinhole and reflected image are both extremely near the optical axis.

The mirrors are set up approximately right by measurement. A ring about an inch in diameter, with two fine threads stretched diametrically across it, one vertical, one horizontal, is set up near the plane of the illuminated pinhole, the intersection of the threads marking the desired position of the optical axis. A light, stiff ring is made, which fits closely over the edge of the paraboloidal mirror, at the front; this ring can be slipped on and taken off as required. Two very fine bright wires are stretched diametrically across this ring, one vertical, one horizontal; these wires should be as close as possible to the face of the mirror; their intersection marks the position of the center or vertex of the paraboloid. Two fine short lines, one vertical, one horizontal, are scratched with a fine needle-point at the center of the silvered face of the small diagonal plane mirror. The eye is now placed about 3 feet outside of the plane of the crossed threads, and an assistant changes the inclination of the small plane mirror, by means of three adjusting-screws at its back, until the intersections of the threads, of the scratches, and of the wires are all seen in exact coincidence. The assistant next changes the inclination of the paraboloidal mirror (by means of three adjusting-screws at its back) until, with the eye in the same position as before, the intersection of the threads, the intersection of the wires, and the *reflection* of the intersection of the threads seen in the paraboloidal mirror, all appear in exact coincidence; the position of the axis of the paraboloid has now been defined. No attention is paid to the large plane mirror in this part of the work. The illuminated pinhole is now placed in position, and the large plane mirror is adjusted (by means of three adjusting-screws at its back) until the reflected image falls in the right position with reference to the axis and pinhole.

The frame which carries the paraboloidal mirror can easily be so designed that this mirror can be removed and replaced repeatedly, while figuring it, without sensibly disturbing the adjustments.

The difficulties of making short-focus paraboloidal mirrors of fine figure are so greatly reduced when this method of testing is used that I believe that the general adoption of this method by opticians would lead to such improvements in results as to bring about a marked advance in the usefulness of reflecting telescopes. The making of the large plane mirror which is necessary in this test becomes so simple

and certain when the methods of testing and figuring described in the preceding chapter are used, that I have no hesitation in saying that when a large paraboloidal mirror of short focus and of the finest attainable figure is to be made, it is economical to make a plane mirror of the same size, with which to test it, if one is not already available. The concave mirror is first figured spherical and is used thus for testing the plane mirror while the latter is being figured; the plane mirror is then used in testing the concave one during the parabolizing of the latter. Both the plane and paraboloidal mirrors are then used in testing the small (convex) hyperboloidal mirror while the latter is being figured.

Testing a Paraboloid on a Star. With this method the mirror surface, as seen with the knife-edge test, presents the same general appearance as in testing in conjunction with a large plane mirror; in the latter test, however, errors of surface are

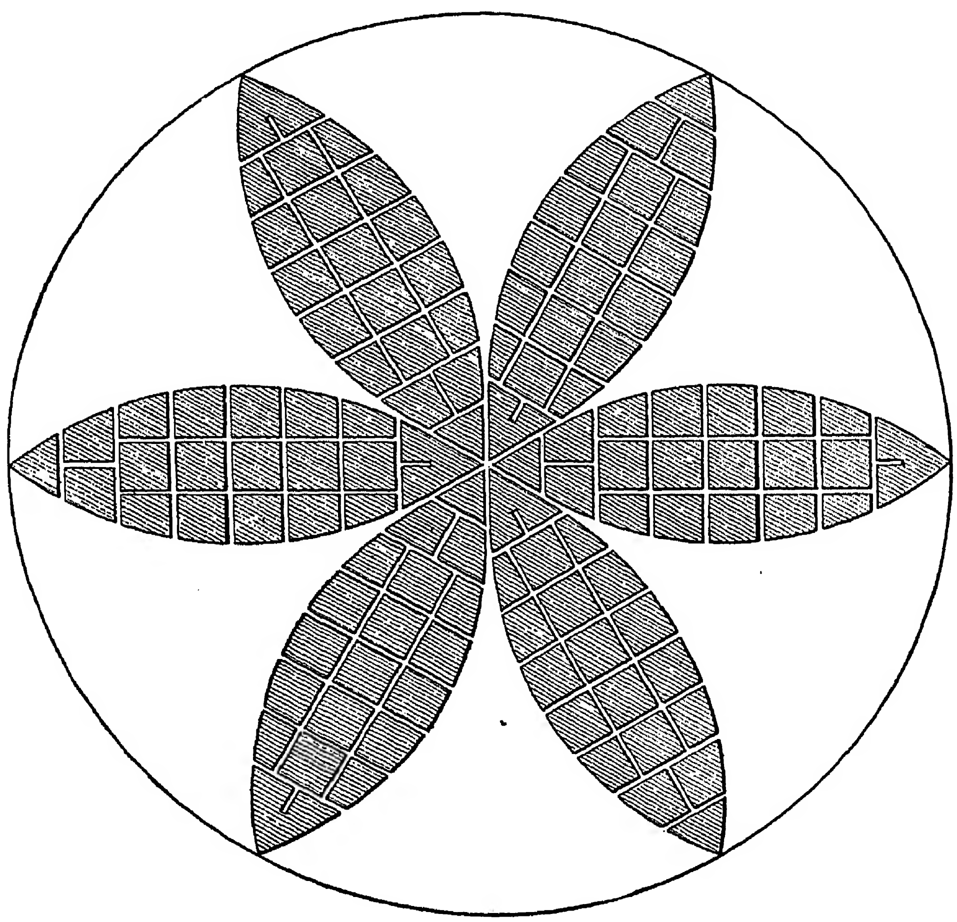


FIG. 13. FULL-SIZE POLISHING TOOL FOR PARABOLIZING.

seen in greater relief, because the effect of such errors is doubled on account of the two reflections from the paraboloid. In addition, it is impossible to overestimate the advantage of being able to test as often as is desired, in the optical laboratory, where atmospheric and temperature conditions can be controlled perfectly, and where the mirror does not have to be removed from the polishing machine in order to test it. In testing on a star it is seldom indeed that atmospheric conditions are sufficiently fine to allow any except the larger errors of surface to be seen.

Changing a Spherical Surface to a Paraboloid. As before stated, this is accomplished by shortening the radii of curvature of all of the inner zones of the sur-

face, leaving the outermost zone unchanged (see Fig. 10). There are two distinct methods of accomplishing this: (1) by the use of full-size polishing tools, the rosin surfaces of which are cut away in such a manner as to give a large excess of polishing surface near the central parts of the tool; (2) by the use of small polishing or figuring tools worked chiefly upon the central parts of the mirror, and less and less upon the zones toward the edge.

(1) *Parabolizing with Full-Size Tools.* The rosin surface can be trimmed in a variety of ways to give a great excess of action on the central parts of the mirror. Fig. 13 shows one of the best forms of tool for this purpose, the shaded parts representing the rosin surface, coated with wax. The form of the edges of the rosin-covered areas can be altered as desired, and thus the amount of action on any zone can be in some measure controlled. Length of stroke and amount of side-throw are also very important factors in controlling the figure of the mirror. Tools of this kind serve admirably in parabolizing mirrors up to 36 or 40 inches in diameter, when the angular aperture is not very great.

(2) *Parabolizing with One-Third-Size and Smaller Tools.* In the case of very large mirrors, when full-size tools are almost unmanageably heavy, and in the case of mirrors of great angular aperture, in which the departure from a spherical surface is great and is effected with difficulty with full-size tools, one-third-size and smaller figuring tools may be used. The machine should invariably be employed in this work, the transverse slide being used to place the tool in succession upon the various zones. In order to preserve the surface of revolution the setting of the transverse slide should be changed only at the end of one or more complete revolutions of the glass. The rosin squares of the small tools should be somewhat softer than usual, so that the surfaces of the tools can accommodate themselves slowly to the slightly different curvatures of the successive zones. The squares around the edges of the tools should be trimmed, as before described, in order to soften the action of the edges. The mirror should be tested very often, and the utmost care taken to keep the apparent curve of the surface, as seen with the knife-edge test, a *smooth* one, *i. e.*, free from small zonal irregularities, at all stages of the parabolizing; this is not extremely difficult when the optician has become experienced in the use of the transverse slide.

The mirror of the 2-foot reflector of the Yerkes Observatory, which has a focal length of only 93 inches, was parabolized in this way by the writer. Two small tools were used, of 6 and 8 inches diameter respectively. The actual difference of depth, at the center or vertex of this mirror, between the paraboloid and the nearest spherical surface is almost exactly 0.0004 inch. This difference is unusually large in this case, on account of the exceptionally great ratio of aperture to focal length. This difference varies, in different mirrors, as the fourth power of the diameter of the mirrors, and inversely as the cube of the focal length. In the case of Lord Rosse's great mirror, in which the aperture is 6 feet and the focal length 54 feet (ratio 1 to 9) the corresponding difference at the center is only 0.0001 inch, very nearly. In the case of the 5-foot mirror of the Yerkes Observatory, of 25 feet focal length, the corresponding difference is about 0.C006 inch. This gives some idea of

the actual amount of glass which must be removed by the figuring tools in parabolizing.

CHAPTER XIV.

TESTING AND FIGURING CONVEX HYPERBOLOIDAL MIRRORS.

THE methods of figuring and rigorously testing convex hyperboloidal mirrors are now so thoroughly developed that the reflecting telescope can be regarded as a universal photographic telescope of the highest class, capable of giving, at the focus of the paraboloidal mirror of large angular aperture, the finest photographs now attainable of large and excessively faint objects such as the nebulæ in general; while by the addition of a small convex mirror a great equivalent focal length is obtained for the photography of bright celestial objects requiring large scale, such as the moon, the planets, the dense globular star clusters, and the annular and planetary nebulæ. The convex mirror of course serves as an amplifier, and possesses the great advantages over a lens used for this purpose that the perfect achromatism and the high photographic efficiency of the reflector are retained, and that the mechanical arrangements are very compact and economical. In order to give perfect definition the convex mirror must be an hyperboloidal one.

The writer has recently made two convex mirrors of different curvature, for use with the 2-foot reflector. These give equivalent focal lengths of 27 and 38 feet respectively.

Fig. 14 shows the arrangement of mirrors employed in the 2-foot reflector when used as a Cassegrain; a small diagonal plane mirror is used at m, to avoid the necessity of a hole through the center of the large concave mirror. P is the paraboloidal mirror, with its focus at f; H is the hyperboloidal mirror, the secondary

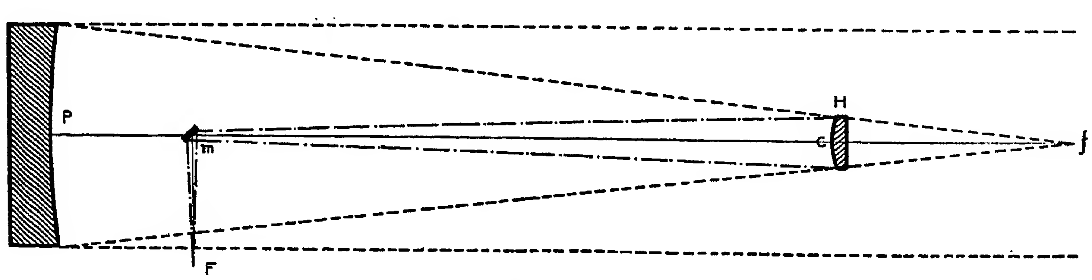


FIG. 14.

focus or magnified image produced by the combination being at F; the point c is the center of the hyperboloidal surface. Calling the distance $fc = p$ and the distance $cm + mF = p'$, then $\frac{p'}{p}$ represents the amount of amplification introduced by the convex mirror. The radius of curvature R of the spherical surface to which the convex mirror is ground and polished preparatory to hyperbolizing is found with sufficient accuracy for all practical purposes by the formula $\frac{1}{p} - \frac{1}{p'} = \frac{2}{R}$ whence $R = \frac{2pp'}{p'-p}$.

For example, let the focal length of the paraboloidal mirror P, Fig. 14, be ten feet; let $fc = p = 2$ ft. and $cm + mF = p' = 8$ ft. Here $\frac{p'}{p} = 4$; the image of the moon or other celestial object produced at F is therefore four times larger in diameter than it would be at f, the focus of the paraboloid; and $R = \frac{2\,pp'}{p'-p} = 64$ inches.

The method of testing the convex mirror while hyperbolizing it is shown in Fig. 15. The illuminated pinhole is placed very near the axis at F. The diverg-

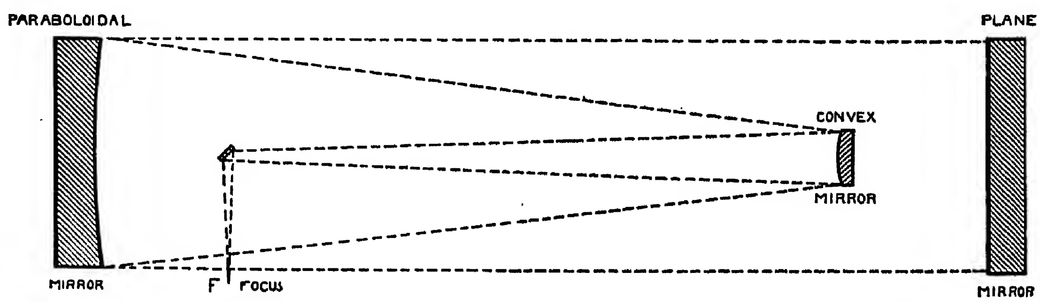


FIG. 15. DIAGRAM ILLUSTRATING TESTING OF HYPERBOLOIDAL MIRROR.

ing cone of light strikes the small plane mirror, then the convex, then the large paraboloid, whence if all of the mirrors are finished and are well adjusted or collimated, the light is reflected in a parallel beam to the large plane; returning, the rays are brought to a focus very near the axis of figure and in the plane of the illuminated pinhole. All of the mirrors except the convex one are silvered. The convex spherical surface with radius of curvature R, as above described, when viewed with the knife-edge test from the point F, presents the same general appearance of a smoothly curved surface of revolution, in strong light and shade, which a paraboloidal surface presents when similarly viewed from its center of curvature (see Fig. 8, p. 33). All that is necessary to produce the hyperboloidal surface is to soften down, with suitable polishing tools, the apparent broad protuberant zone between the center and edge, until the mirror, as seen from F, appears perfectly flat; *i. e.*, until the illuminated surface is seen to darken with absolute uniformity all over when the knife-edge is moved across the focus. This hyperbolizing may be done with small local or figuring tools, or with a full-size tool so trimmed as to give an excess of action on the broad zone a, or (what is usually best) by a combination of the use of both kinds of tools.

As in the case of the paraboloid, it is necessary in this test that all of the mirrors be lined up or collimated with care; otherwise the surface of the convex mirror will not appear as a surface of revolution, and cannot be properly tested. The axes of the paraboloid and hyperboloid must coincide, and the face of the large plane mirror must be at right angles to these axes. These adjustments are made by means of an extension of the method of collimation described in the preceding chapter, p. 35. First the paraboloidal mirror is adjusted so that its axis intersects the hyperboloid at its exact center or vertex; in making this adjustment fine threads are stretched diametrically across the cell of the convex mirror, this

mirror being removed during this part of the adjustment. Next, the small diagonal plane is adjusted for inclination, care being taken that the intersection of the lines scratched in its film is placed in the axis of the paraboloid. Then the convex mirror is adjusted for inclination, by reflection. Finally, with the illuminated pin-hole in place, the large plane mirror is adjusted, as previously described.

CHAPTER XV.

SILVERING.

It is not my purpose to discuss the various processes of silvering. Several methods have been admirably described by Draper (see p. 2 of his book), by Brashear, and by Common (see p. 159 of his paper *On the Construction of a Five-Foot Reflecting Telescope*). I have used almost exclusively the formula published by Brashear in 1884, in which sugar is the reducing agent. After experience with this process, and when the grades of chemicals specified below are used, silver films are invariably obtained which take a perfectly black polish, and which are so thick as to be nearly opaque even to the sun's disk. Small mirrors are usually silvered face down; films which are satisfactory in all respects are obtained when this is done.

In the case of large mirrors it is more economical of silver, as well as safer and more convenient in manipulation, to silver face up. Two difficulties occur, however, when this is done; first, minute transparent spots are liable to occur in the film; these are so small, however, that they can be seen only when looking through the film at a bright object; second, the refuse silvering solutions must be poured off the mirror, after the silver has been deposited, at exactly the right stage of the reaction; if poured off too soon the film will be thin; if too late, the muddy-brown precipitate which settles upon the film will slightly tarnish the latter in such a manner that it will not take a perfect polish; it is only by experience that the optician is able to determine the right instant for pouring off the refuse solutions. Mr. Common encountered similar difficulties in silvering face up, and resorted to the use of solutions without caustic potash, and also to the use of Draper's method of reducing with Rochelle salt; these methods, while subject to their own special difficulties, do not give the objectionable precipitate. The writer has adhered to the use of a slight modification of Brashear's formula already mentioned, in part because no opportunity has occurred for comparing thoroughly the merits of the various formulæ, and in part because the films obtained by this method give entire satisfaction in use.

The Reducing Solution. This consists of distilled water, 200 parts; loaf-sugar or pure rock-candy, 20 parts; alcohol (pure) 20 parts; nitric acid (c. p.) 1 part. The proportions given are by weight. This solution is greatly improved by keeping, a solution which has been made for several months working more surely than one newly made. A gallon of this solution is usually made at one time.

The operation of silvering a 2-foot mirror face up will now be described. It will be assumed for the present that the back of the mirror is unsilvered. A silvering table is used, which is a strong structure of oak wood having a tilting frame carried on two trunnions, so that the mirror can be quickly turned from a horizontal to a vertical position, for the purpose of pouring off the cleaning and silvering solutions; a strong narrow edge-band of flexible steel prevents the mirror from sliding off; the tilting frame is heavily weighted below so that it cannot turn down accidentally. Thus all handling of the mirror while silvering is avoided.

The old silver film, if one exists, is removed with strong nitric acid on a bunch of absorbent cotton tied to a glass rod. The face and edge of the mirror are then quickly washed with distilled water. A band of strong brown drawing paper, which has been dipped in melted paraffin, is drawn around the edge of the glass and tightly bound to it by means of a thin band of copper with tightening screws; the paper should project about three inches above the glass; the joints should all be made water-tight by means of more paraffin and a warm iron. A dish about three inches deep is thus formed, with the mirror as its bottom.

A 10 per cent solution of pure caustic potash in distilled water is now used for thoroughly washing the face of the glass and the inside of the paraffin band; this is done with a large bunch of absorbent cotton tied to a glass rod. This solution is then poured out and the glass is similarly washed several times with fresh supplies of distilled water, to get rid of all traces of potash. Enough distilled water is now poured on the glass to entirely cover it while the silvering solutions are being mixed.

All of the vessels, graduates, etc., used for mixing the silvering solutions, must be thoroughly washed, first with nitric acid, then with caustic potash, and rinsed with distilled water, just as the mirror is cleaned.

For silvering the face of a 2-foot mirror, 2 ounces of silver nitrate (Powers & Weightman) are dissolved in 20 ounces of distilled water. One and one-third ounces of caustic potash, pure by alcohol (Merck), are dissolved in 20 ounces of water in a separate vessel, and the solution is cooled. Strong aqua ammonia (pure) is added, drop by drop, to the nitrate solution, while the liquid is thoroughly stirred; the mixture turns light-brown, then dark-brown; the ammonia is slowly added until the liquid becomes clear. The caustic potash solution is now added slowly, with thorough stirring; the mixture now becomes very dark-brown or black. Ammonia is again added, with thorough stirring, until the liquid again just clears. A solution of one-fourth ounce silver nitrate in 16 ounces of distilled water having been prepared, this is added to the mixture, a few drops at a time, with thorough stirring, until the entire solution has a decided straw color, while remaining transparent. This straw color is the test for the condition of instability which is absolutely necessary in order that the metallic silver shall be thrown out of combination when the reducing solution is added later. The solution is now thoroughly filtered through absorbent cotton.

A quantity of reducing solution is taken containing an amount of sugar equal

in weight to one-half that of the entire amount of silver nitrate used; this is also filtered. The silver solution and reducing solution are now both diluted with distilled water, preparatory to mixing; the quantity of the diluted solutions, together, should be sufficient to cover the glass about one inch deep.

An assistant pours off the water which has stood on the glass, while the optician quickly mixes the dilute silver and reducing solutions in a large pitcher or granite-ware bucket. The glass being horizontal, the mixed solution is immediately poured on, and the mirror is rocked slightly by means of the tilting frame. The liquid quickly changes to a transparent light-brown color, then dark brown, then black, after which the silver immediately begins to deposit. The solution gradually changes to a muddy-brown color, and in three or four minutes after the solutions are poured on the glass, begins to clear; the light muddy-brown precipitate settling upon the film. With the proportions given, the silver film should be sufficiently thick in about five minutes after the solutions are poured on the glass provided that the room, glass, and solutions are all at a temperature of sixty-eight degrees or seventy degrees Fahrenheit. When first formed the brown precipitate is so light that it moves about with the rocking of the glass; but it very soon deposits in large areas on the film. As soon as this begins to occur, the solution must be very quickly poured off the glass, an abundance of distilled water poured on, and a large bunch of absorbent cotton, held in the fingers, instantly used to displace all streaks of the precipitate which adhere to the film. The film is now washed again and again with fresh distilled water and a soft bunch of cotton; then an abundance of water is poured on and the film allowed to soak for an hour. When this is poured off, the paper band is carefully removed, with the glass horizontal so that no liquid from the edge can run upon the silver film; this must be done quickly, before the latter has time to dry. A small amount of alcohol is now flowed on the film; this is repeated several times to get rid of all water; the glass is then turned on edge, and is quickly dried with a fan.

After standing for an hour or two in a dry room the film is to be burnished. A soft pad as large as the hand is made of the softest chamois skin; this is used on the film without rouge, with light circular strokes, to condense the silver. After two hours of this work a little of the finest washed dry *jeweler's* rouge is rubbed into the chamois-skin with a piece of clean absorbent cotton; from thirty to sixty minutes use of the pad with the same stroke as before should now bring the film to a perfect polish, without scratches.

If the back of the mirror is already silvered, the face can be silvered by the method just described, without injuring the film on the back; the mirror now rests upon three curved and beveled blocks of soft wood which touch only the rounded corner or edge of the back of the glass; extra precautions are now taken to prevent any of the solution from touching the back. I regard this method as much better in the case of large mirrors than to attempt to silver both back and face at the same time in a deep tray; in the latter method the difficulties of handling and properly cleaning the mirror are almost insurmountable.

The back of the mirror does not usually need silvering oftener than once in

three or four years. The face is usually silvered two or three times a year, to keep it in the finest condition for photography, in which any yellowing of the film is very objectionable.

CHAPTER XVI.

A SUPPORT-SYSTEM FOR LARGE MIRRORS.

THE proper support of mirrors in their cells when in use in the telescope is a matter of vital importance. Small mirrors can be made very thick and can be supported at their edges as a lens is supported; the cell must be so designed that no sensible change of position of the mirror in its cell can occur. The necessity of supporting large mirrors in such a manner as to prevent flexure from their own weight, in all positions which can occur in use, has long been recognized, and elaborate support-systems for this purpose have been devised and used by Rosse, Grubb, Common, and others. Comparatively little attention has been given, however, to two additional requirements which are no less important; first, the position of the mirrors in their cells should be defined with the greatest attainable stability, in order to secure permanence of adjustment or collimation; second, the method of support should be such that the silvered back of the mirror is exposed to the air as freely as possible. It is assumed that a large mirror need never be turned farther than ninety degrees from the position in which it lies horizontal upon its back.

In the *Astrophysical Journal* for February, 1897, the writer described a method of supporting large mirrors which fulfills all of the requirements named in the preceding paragraph. I have employed this method in the designs for the support-system of the 5-foot mirror. These designs are described and illustrated here.

I.—*The Back-Support.*

Let us consider the mirror to be divided into twelve imaginary segments of equal weight, as shown in Fig. 16, Plate VIII. The back of the mirror rests, primarily, upon three strong bronze plates, each ten inches in diameter, represented by the double circles *a* Fig. 16 and at *a* Fig. 17, the center of each plate being exactly behind the center of weight of the corresponding segments; these are called the stationary plates. The upper surface of each plate is flat and is ground to fit the flat back of the glass; the lower surface is spherical, and is ground to fit the large spherical socket in which it rests. It will be noticed that these plates are near the edge of the mirror, in the outer ring of segments; the base of stable support is therefore large. It is evident that by properly designing these plates and their supports we can fix with very great stability the plane of the mirror which rests directly upon them; there is no building out from the three primary points of support by means of intermediate levers and triangles, as in the older systems.

The weight of the remaining nine segments of the mirror is just balanced by means of nine weighted levers, each of which is entirely independent of every

other, which lie in a plane parallel to the back of the mirror. One of these levers is shown in elevation at *c*, Fig. 17, and in plan in Fig. 21. The positions of the nine levers are indicated by dotted crosses in Figs. 16 and 18. These levers are suspended between pivots screwed through lugs connected to the cell. The cone bearings, shown in Fig. 21, are finely fitted, and are ground to reduce friction. The long arms of the levers carry adjustable lead weights (*d* Figs. 17 and 21) which are made in the form of plates, in order that they may occupy as little space as possible perpendicular to the plane of the mirror; the short arms of the levers are thus made to press against the backs of the corresponding segments through the medium of light plates of bronze represented by the single circles *b* Fig. 16 and at *b* Figs. 17 and 21.

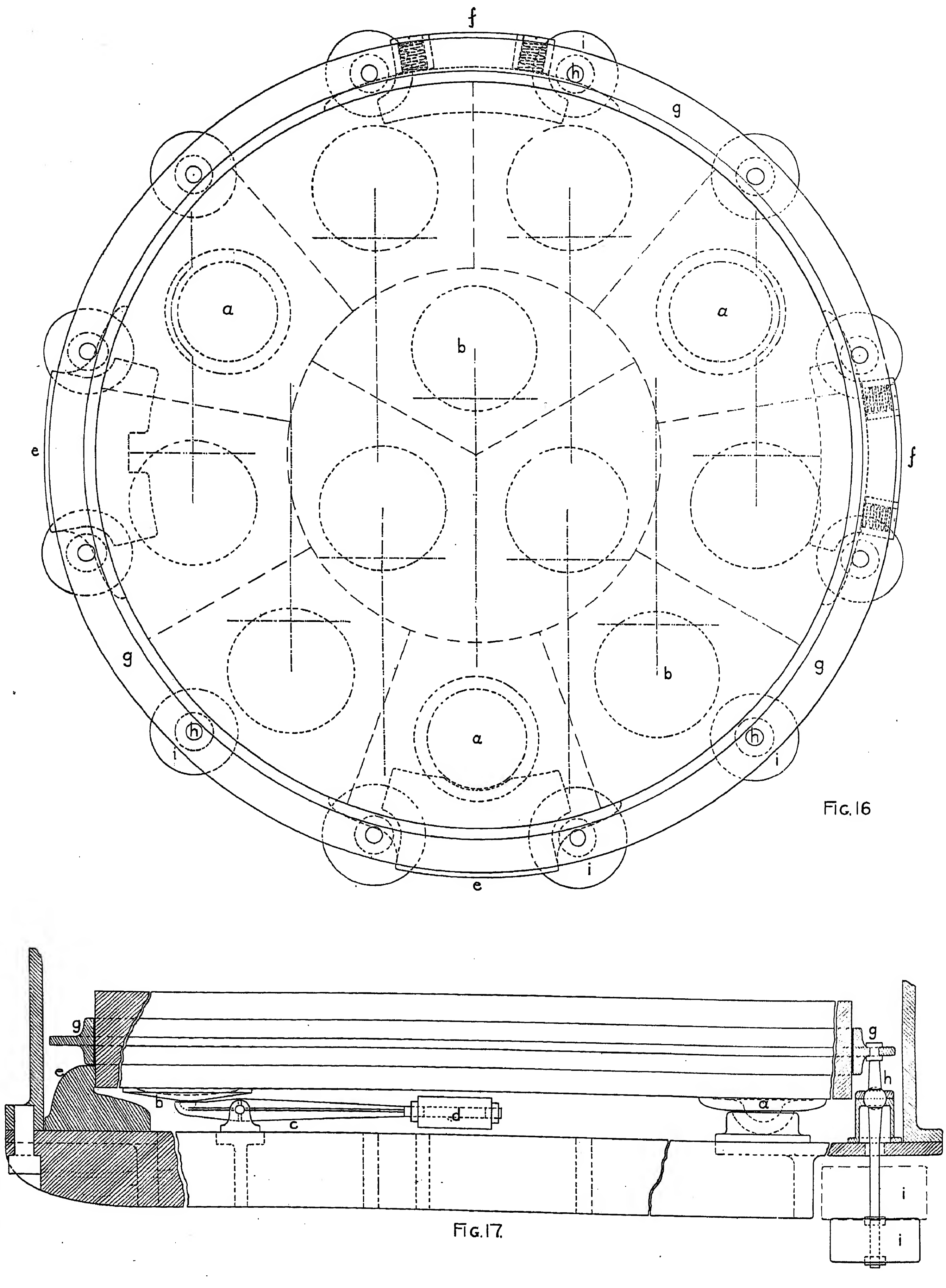
The large mirror weighs very nearly 2000 pounds, so that each segment weighs $166\frac{2}{3}$ pounds. With the cell in a horizontal position the lead weight on each arm is adjusted until it just balances a standard weight of $166\frac{2}{3}$ pounds placed upon the plate on the short arm. This adjustment being completed the mirror is laid upon the support-system; three-quarters of its weight is carried by the nine levers, leaving one quarter to be divided equally between the three heavy plates *a*. Thus each of the twelve segments is entirely supported at the back, independently of all of the other segments. Now suppose that the edge-support, which will be described below, be introduced, and the entire system, with the glass, inclined in any direction and at any angle; all of the levers and weights retain the same position as before with reference to the glass, but they do not exert the same pressure, on account of the inclination; so far as the back-support is concerned there will still be a perfect balance maintained in the case of each segment; this is true whatever point of the edge of the mirror becomes lowest—*i. e.*, in whatever direction the levers lie with respect to the vertical plane through the axis of figure of the mirror.

It should be noticed that in the case of each of the twelve 10-inch supporting plates only a ring one inch wide around the edge is in contact with the glass; the part of each plate inside of this ring consists of deep, narrow arms, which do not touch the glass, and which allows free access of air to the latter.

For very large or thin mirrors a larger number of plates and levers can of course be used. An incidental advantage which occurs when this is done is that the base of stable support afforded by the three stationary plates is still larger, compared with the size of the mirror, than when twelve plates are used.

II.—*The Edge-Support.*

The relation between the back-support and edge-support is so intimate that any inefficiency in the latter must injuriously affect the operation of the former, however perfect that may be in itself. In an equatorial reflecting telescope, different parts of the edge of the mirror become successively lowest, as the position of the telescope changes. With the flexible band and cushioned edge-support so much used in the past, the heavy mirror necessarily changes its position, laterally, with



SUPPORT SYSTEM FOR LARGE MIRROR.

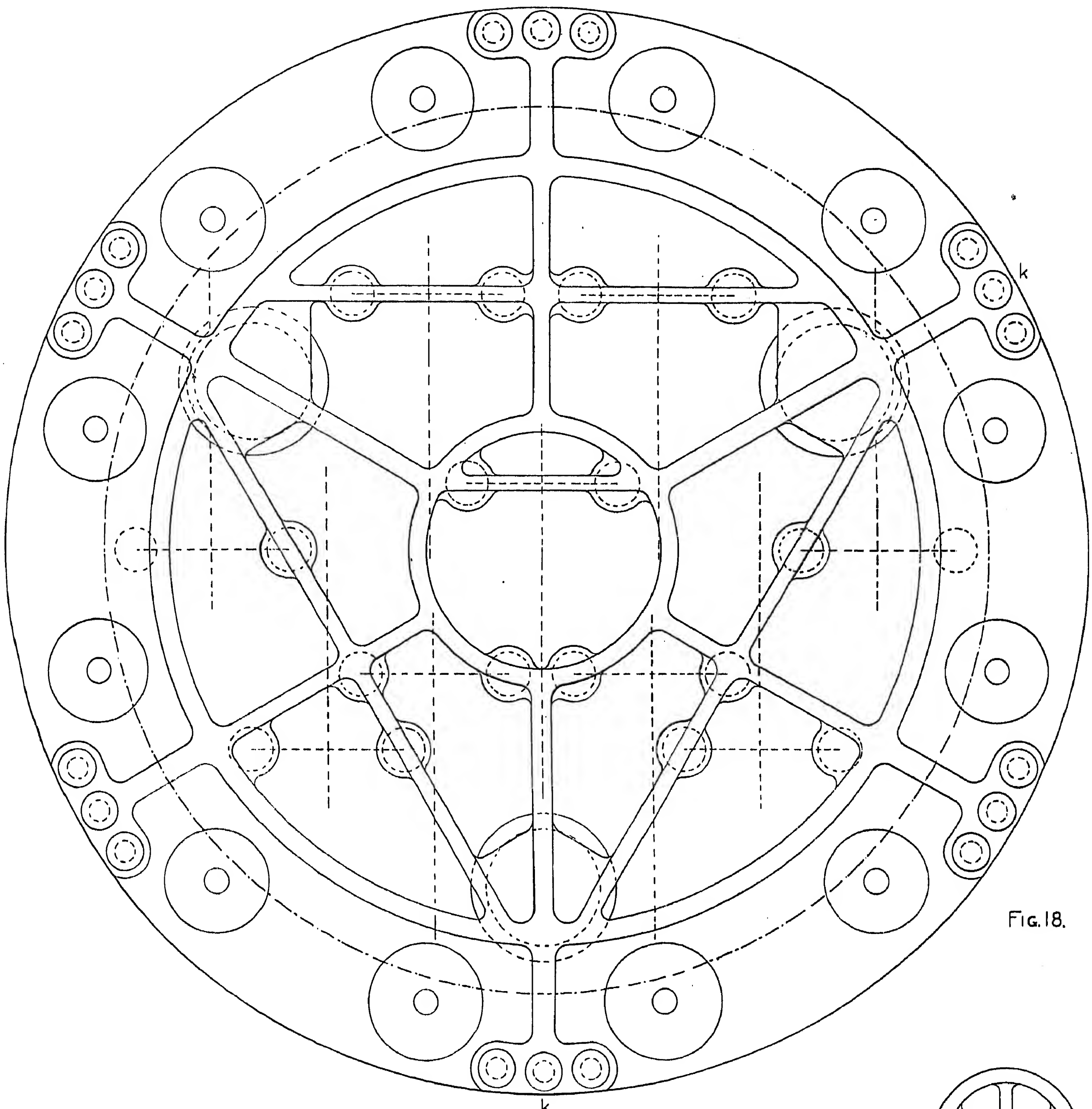


FIG. 18.

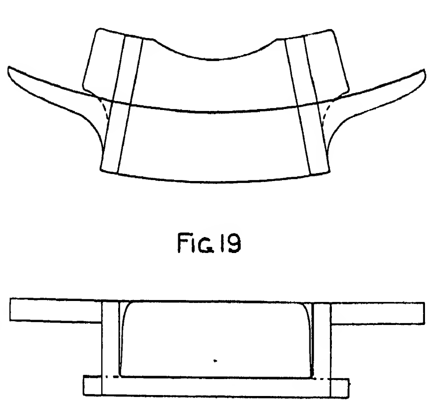


FIG. 19

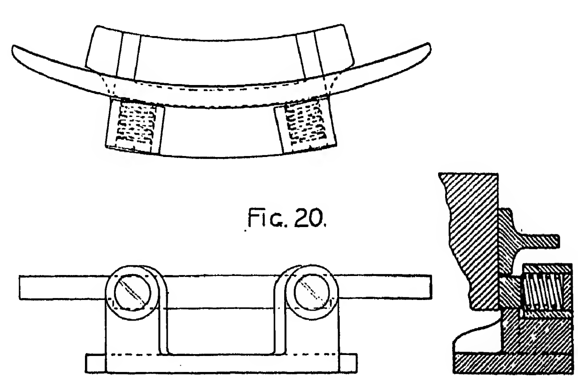


FIG. 20.

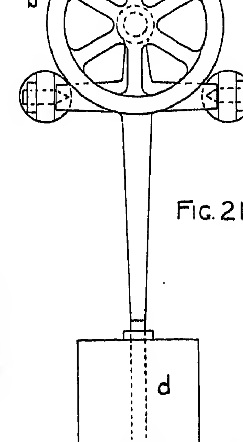


FIG. 21

SUPPORT SYSTEM FOR LARGE MIRROR.

respect to its cell, in taking its position down against the edge-support; thus not only is permanence of position lost, but this tendency to lateral shift must impair the freedom of operation of the back-support system.

In the present plan four metal arcs are used which rigorously define the position of the mirror laterally. Two of these arcs (*e* Figs. 16 and 17, and Fig. 19), adjacent to each other, are bolted down to the cell, and their inner edges are scraped to fit the ground edge of the glass; these are called the stationary arcs; the other two arcs (*f* Fig. 16 and Fig. 20), diametrically opposite the stationary ones, exert a slight pressure against the edge of the mirror, by means of springs, for the purpose of seating the mirror against the stationary arcs and holding it there; this pressure need amount to only a very small percentage of the mirror's weight, for all of the lateral pressure due to the weight of the mirror when the latter is inclined is carried by a strong metal *counterpoising ring* of T section (*g* Figs. 16 and 17); this completely encircles the edge of the mirror, and fits it loosely, a band of leather or thick felt paper being inserted between the ring and the glass. For convenience in description, imagine this ring to be suspended from the tube above, by means of three short wires, so that if the mirror were removed the ring could swing freely in its own plane. The ring is pressed up against the edge of the mirror, when the latter is inclined, by a system of twelve short weighted levers (*h* Figs. 16 and 17) which hang perpendicular to the plane of the ring. These levers are suspended from the cell-plate behind the ring, by means of ball-and-socket joints, as shown in Fig. 17, or preferably, to reduce friction, on pivoted universal or Hooke's joints. The ends of the short upper arms of these levers fit loosely into holes in the ring; the long lower arms carry lead weights (*i* Figs. 16 and 17) which are capable of slight adjustment.

Assuming that the counterpoising ring weighs 400 pounds, so that the combined weight of ring and mirror is 2400 pounds, the adjustment of the edge-support levers is effected by turning the entire cell to a vertical plane, with the mirror and ring removed, and adjusting each of the twelve lead weights until it just balances a standard weight of 200 pounds hung on the short arm of the lever at the point where this is to touch the ring.

I regard the use of a support-system which will fulfill all of the conditions mentioned at the beginning of this chapter as absolutely essential for large mirrors. Only those who have tested large mirrors and combinations of mirrors in the optical shop, and those who have actually used large reflecting telescopes, can fully appreciate the necessity of a support-system which will both support the mirrors without constraint and flexure, and define their positions permanently with respect to the tube and axes, in all positions of the telescope. These conditions can now be attained easily and economically; without them it is folly on the one hand to expect good definition and successful photographs, or, on the other hand, to complain that the reflecting telescope is subject to serious inherent difficulties which cannot be overcome. In the case of large mirrors in which the ratio of thickness to diameter is not less than as 1 to 9 or 1 to 10 the support-system just described floats the mirror so perfectly in all positions which can occur in actual use that no

flexure or distortion can be detected with the most sensitive optical tests. Furthermore, with the method of edge-support described, and in the case of the 5-foot mirror weighing a ton, no lateral shift amounting to $\frac{1}{2000}$ inch can occur when the mirror is turned in extreme oblique positions.

In Figs. 17 and 18 is shown the massive cell-plate of cast-iron which carries the mirror and its support-system, and which is connected to the short cast-iron section of the tube; this connection is made by means of strong adjusting screws, by means of which the mirror and its support-system, as a whole, are adjusted for collimating the mirror; these adjusting screws are shown at *k*, Fig. 18. Additional screws are also shown at *l* in this figure; these are backed out of the way when collimating is being done; when this is finished they are brought into position, and assist in bolting the cell-plate rigidly to the tube. As is shown in Figs. 17 and 18, the central part of the cell-plate, a circle about 50 inches in diameter, consists of open ribs or arms which allow free access of air to the silvered back of the mirror.

When the face of the mirror is to be resilvered, the cell-plate, support-system, and mirror are removed as a whole, and silvering is done in the manner described in the preceding chapter, without taking the mirror from its supports or disturbing the adjustments of the latter in any way. Furthermore, the mirror can be taken out of the telescope in this way, silvered, and replaced, without sensibly disturbing its collimation or the position of the focal plane. When the back of the mirror must be resilvered, which need not be done oftener than once in three or four years, the glass must of course be removed from its support-system.

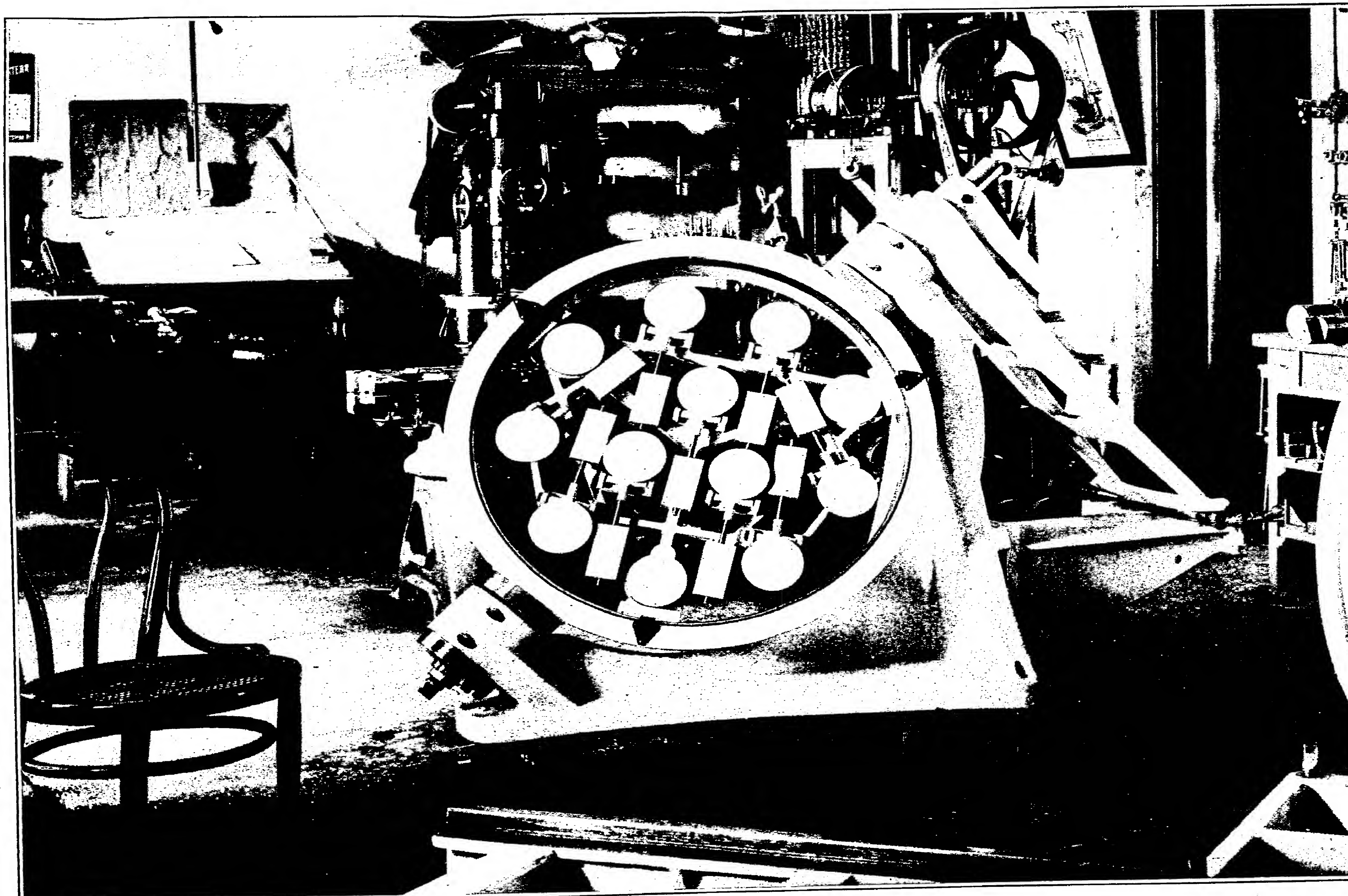
This support-system, as described, may appear complicated and expensive; in reality it is not so, for all of the levers, plates, etc., used for the back-support can be exactly alike, as can also the levers used for edge-support; even when a greater number of levers than twelve are used the construction is simple and economical.

In Plate x is shown a 30-inch plane mirror supported at the back by twelve plates and nine levers as described above; the mirror is shown unsilvered, so that the plates are seen through 4 inches of glass. This is a part of the 30-inch cœlostat recently constructed from the writer's designs in the instrument and optical shops of the Yerkes Observatory.

CHAPTER XVII.

A MOUNTING FOR A LARGE REFLECTING TELESCOPE.

In considering the requirements for a modern reflector mounting for photographic and spectroscopic work, the writer can probably not do better than to describe the designs for the proposed mounting of the 5-foot reflector. These designs are the result of experience both in optical work and in the use of the 2-foot reflector and the 40-inch refractor of the Yerkes observatory in astronomical photography.



LARGE COELOSTAT WITH 30-INCH PLANE MIRROR.
PLATES AND LEVERS FOR BACK-SUPPORT ARE SEEN THROUGH THE UNSILVERED GLASS.

With the present great improvements in the materials and methods of machine construction there is no longer any excuse for unstable and inconvenient mountings for reflectors. The focal length of modern reflectors intended for photography is short; the ratio of aperture to focal length generally used in such instruments will probably be not greater than as 1 to 4, nor less than as 1 to 6; with such ratios the mounting can be made extremely compact and rigid. By the addition of a small convex mirror the equivalent focal length can be increased from three and one-half to five times, and fine definition retained; when this is done the actual length of the tube is less than when the telescope is used at the primary focus.

The reflecting telescope defines well only at or near the optical axis; hence the mirrors must remain in perfect adjustment with reference to each other and to the eyepiece or photographic plate, in all positions of the telescope which can occur in use. Not only must the mirror supports be such as to define the position of the mirrors rigorously always, as described in the preceding chapter, but the short tube must be excessively strong and rigid so that no sensible flexure can occur. This is especially necessary when the telescope is used as a Cassegrain, or as a *coude;* for when these forms are employed it is only when the axes of the paraboloid and hyperboloid coincide that fine definition can be secured. When the necessity of these conditions is fully realized by makers and users of reflectors, a marked advance in the usefulness of reflecting telescopes will result. It was the lack of such rigidity and of such permanence of adjustments, fully as much as the lack of means of rigorously testing the optical surfaces, which made the old Cassegrain reflectors, including the great Melbourne instrument, such lamentable failures. I consider the failure of the Melbourne reflector to have been one of the greatest calamities in the history of instrumental astronomy; for by destroying confidence in the usefulness of great reflecting telescopes, it has hindered the development of this type of instrument, so wonderfully efficient in photographic and spectroscopic work, for nearly a third of a century.

When the telescope is to be used for photography, either direct or spectroscopic, it is indispensable that the mounting be so designed that reversal is not necessary when passing the meridian; for it is frequently necessary to expose for six or eight hours without reversal, on faint objects; and the best part of such an exposure is that in which the celestial object is near the meridian. Several forms of reflector mounting have been devised in which reversal is not necessary; the well-known English closed-fork mounting is one of them.

In designing the proposed mounting of the 5-foot reflector of the Yerkes Observatory, of twenty-five feet focal length, the writer has adopted the form in which a short open fork is used at the upper end of the polar axis. The tube hangs between the arms of this fork, being carried on two massive trunnions; the heavy lower end of the tube is so short that it can swing through, between the arms of the fork, for motion in declination.

The fork mounting presents several marked advantages with respect to compactness and stability, as well as convenience and economy, over all forms which are modifications of the German equatorial mounting, in which the tube is carried

out at one side of the equatorial head. The tube, carrying the great weight of the mirror and its cell, is here supported at two opposite sides, instead of from one side only, as in the German forms; no heavy counterpoises are required; this form is much better adapted for the *coude* arrangement of mirrors, so essential in work with very large spectroscopes, only three reflections in all being necessary for this arrangement; furthermore, when the instrument is used at the primary focus, the upper end of the tube is more easily accessible, in all positions of the instrument, from an observing carriage attached to the inside of the dome.

The weight of the moving parts of the telescope will be about twenty tons. On account of this great weight, and also of the overhang of the fork above the bearings of the polar axis, an efficient anti-friction apparatus for the polar axis is demanded, which will at the same time relieve the effect of the overhanging weight of the upper end of the polar axis. The advantages afforded for this purpose by mercury flotation, when this is properly applied, are so great, and the mechanical details for such flotation work out so simply and economically, that this method will undoubtedly be used.

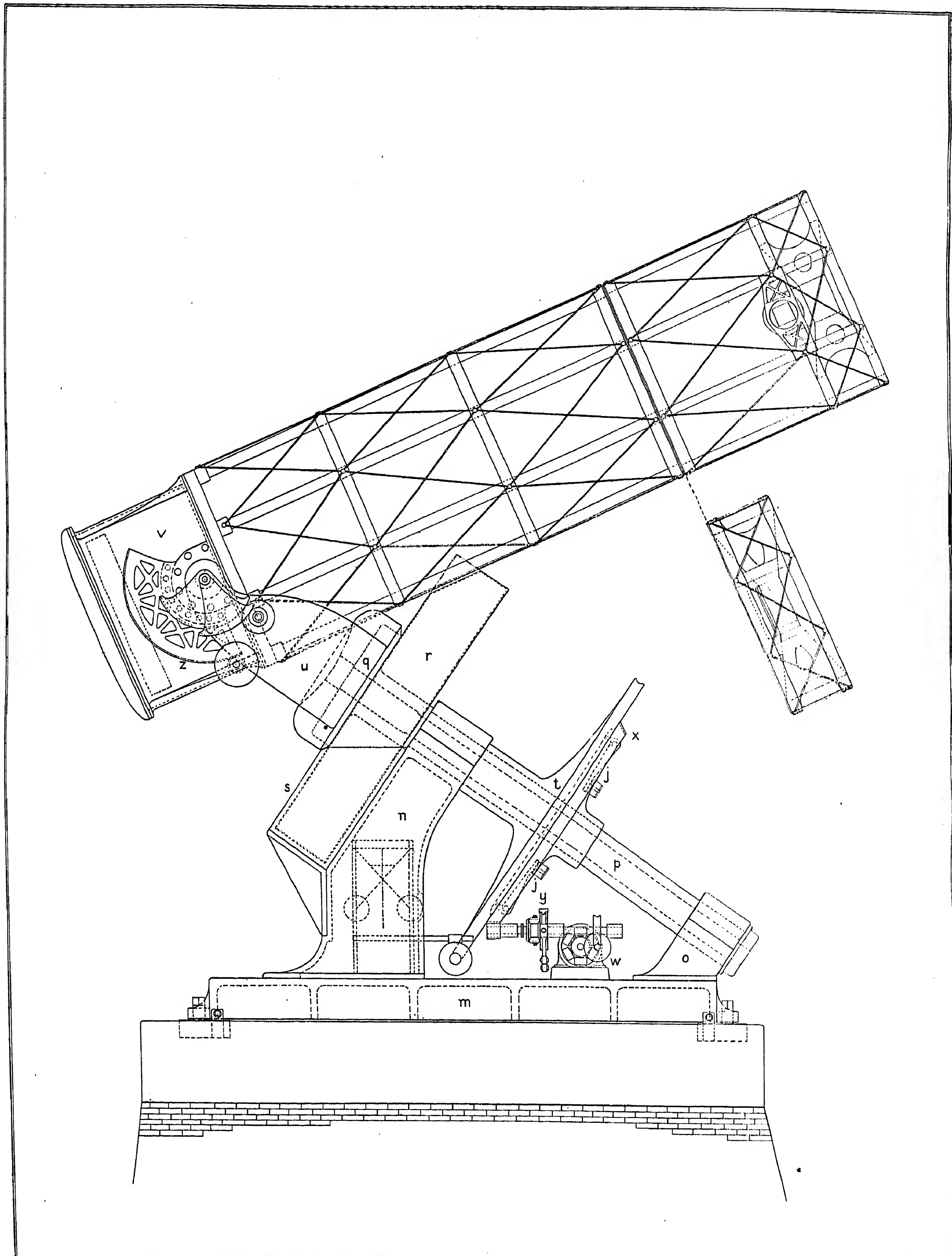
The proposed mounting will now be briefly described in detail, and attention will be called to many points which are indispensable to the success of a reflecting telescope to be used for photography.

The equatorial head consists of three iron castings, the triangular base-plate *m*, Plate XI, and the two posts *n* and *o*, which carry the bearings for the polar axis. Both posts are hollow, with walls $1\frac{3}{4}$ inch thick, and are bolted and pinned to the base casting; the post *n* contains the large driving clock.

The polar axis *p* is of hydraulic-forged steel, with a head or flange *q*, 48 inches in diameter and 7 inches thick, forged upon it; the axis is $14\frac{1}{3}$ feet long over all, is 20 inches in diameter for a distance of 2 feet below the head, and is 16 inches in diameter for the remaining $11\frac{2}{3}$ feet of its length; the axis is hollow, with walls $4\frac{1}{2}$ inches thick. The bearings of the polar axis are of hard Babbitt metal, and are halved.

Attached to the lower surface of the 4-foot head of the polar axis is the large hollow disk or float *r*, 10 feet in diameter and $22\frac{1}{2}$ inches thick or deep; this is constructed very strongly of angle steel covered with steel plates $\frac{3}{8}$ inch thick; the whole is finished smooth on the outside, and is turned true in a lathe. The corresponding trough *s* is of cast-iron and is turned true on the inside. The inner surface of the trough is separated by $\frac{1}{8}$ inch all around from the outer surface of the float; this space is filled with mercury. With the dimensions given the immersed part of the float displaces about 45 cubic feet of mercury, which thus floats about nineteen tons, or 95 per cent of the weight of the moving parts of the telescope. The center of flotation is vertically below the center of weight of the moving parts. Only three-quarters of a cubic foot of mercury is required to float nineteen tons in this manner.

The importance in astronomical photography of the smoothness of motion afforded by really efficient flotation of the moving parts cannot be overestimated. The great size of the worm-wheel *t* which rotates the polar axis, will materially



DESIGN FOR MOUNTING OF FIVE-FOOT REFLECTING TELESCOPE.

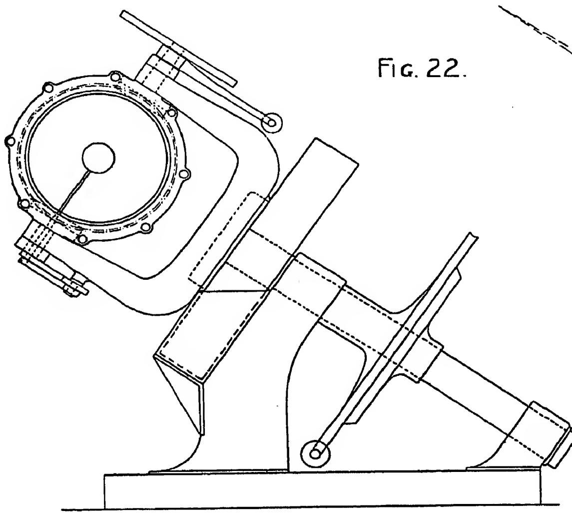


Fig. 22.

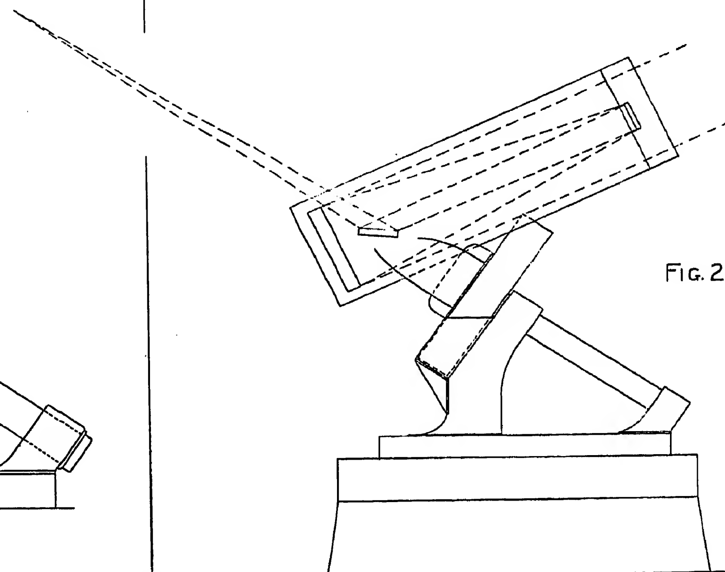


Fig. 27.

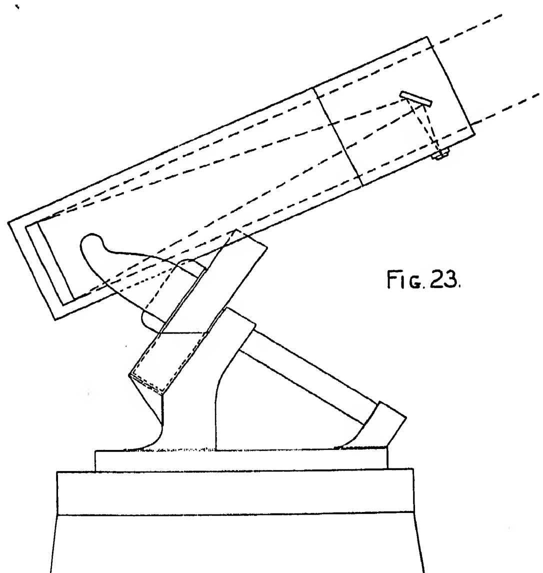


Fig. 23.

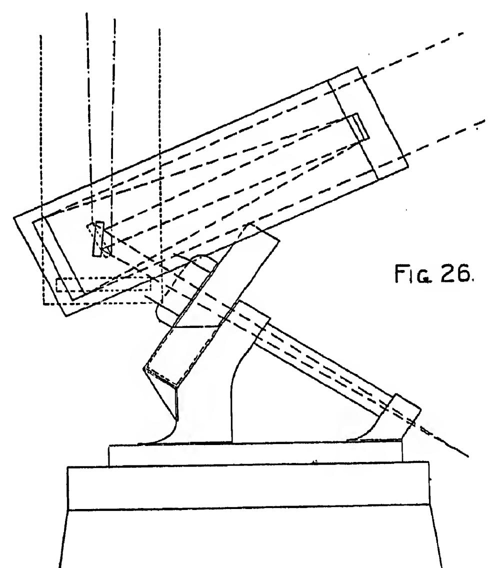


Fig. 26.

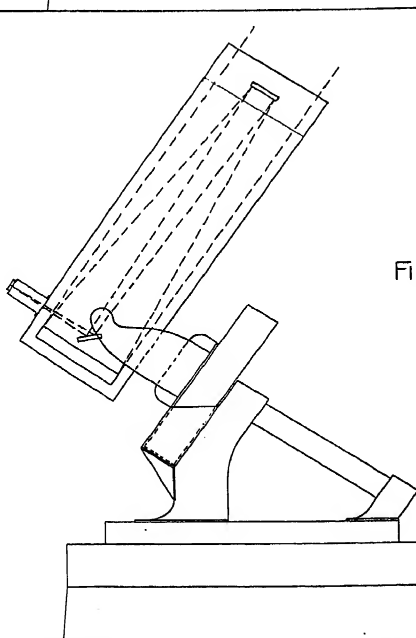


Fig. 24.

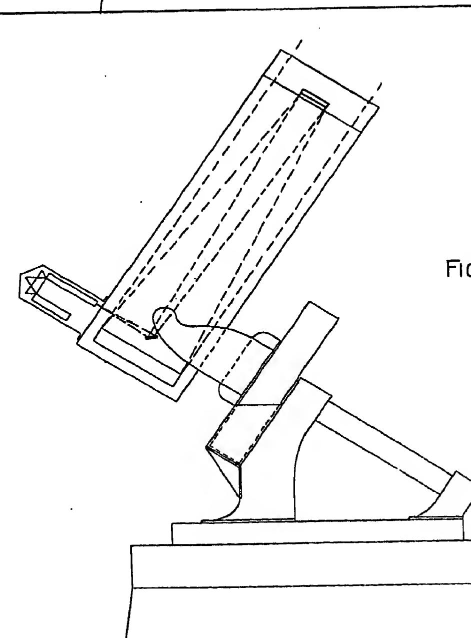


Fig. 25.

DESIGN FOR MOUNTING OF FIVE-FOOT REFLECTING TELESCOPE.

assist in giving smoothness and accuracy of driving; this worm-wheel is 10 feet in diameter.

Attached to the upper surface of the 4-foot head of the polar axis, by means of a circle of 2-inch bolts, is the large cast-iron fork *u*, different views of which are shown in Plate XI and Fig. 22, Plate XII. The extreme outside width of this fork is $8\frac{1}{3}$ feet; it is of hollow or box section, with walls averaging $1\frac{1}{2}$ inches thick; it weighs about five tons.

Between the two arms of the fork hangs the short round cast-iron section *v* of the tube; two 7-inch steel trunnions, having large heads or flanges, are bolted to this casting, and turn in bronze bearings at the upper ends of the fork arms; this part of the tube is 46 inches long; its inside diameter is 70 inches; its thickness is 1 inch; it is reinforced at top and bottom by flanges. To the lower flange is connected the cell-plate (described in the preceding chapter) which carries the large mirror and its support-system.

To the upper flange of the short cast-iron section of the tube is bolted a strong cast-iron ring which forms the lower end of the main or permanent section of the octagonal skeleton tube; this section is 13 feet 11 inches long, and 6 feet 8 inches outside (diagonal) diameter. It is constructed of eight 4-inch steel tubes, connected by strong rings designed to resist compression; diagonal braces, which are connected together at all intersections, greatly increase the rigidity of the structure. This entire section is so rigid that it can be placed in a large lathe for facing the ends parallel to each other, and for turning a slight recess in the ends for the purpose of accurately centering the parts which are to be connected to them.

To the upper end of the permanent section of the skeleton tube can be attached any one of three short extension tubes or frames, as desired; two of these are shown in Plate XI. The lower end of each extension is turned true, with a projecting ring which fits into the turned recess in the upper end of the permanent section. With this arrangement the various extensions can be removed and replaced without sensibly affecting the adjustments of the mirrors and other apparatus which they carry, with reference to the optical axis of the large mirror.

The extension which is shown in place on the telescope in Plate XI and in Fig. 23, Plate XII, is the longest one; it is 6 feet 11 inches long; it is used for all work at the primary focus of the telescope; it carries the diagonal plane mirror and its supports, and the eyepiece and double-slide plate-carrier. This extension can be rotated upon the turned end of the permanent section, so that the eyepiece or photographic apparatus can be brought to the side of the tube which is most convenient for observing or photographing a given object. The diagonal plane mirror is of the finest optical glass, is elliptical in outline, is 15 x 22 inches in size, and is $3\frac{1}{2}$ inches thick; it is carried in a strong cast-iron cell, which is supported from the skeleton tube by four thin steel plates, as shown in Plate XI. The diagonal plane mirror is sufficiently large to fully illuminate a field 7 inches in diameter at the primary focus. The double-slide plate-carrier is designed for $6\frac{1}{2}$ x $8\frac{1}{2}$ inch photographic plates.

The other two extensions of the tube, which are only about 2 feet long, are

employed when the telescope is used as a Cassegrain and as a *coude* respectively; each carries a convex mirror 19 inches in diameter and $3\frac{1}{6}$ inches thick, of the finest optical glass, and of the proper curvature for the purpose desired.

Figs. 24 and 25, Plate XII, show the telescope used as a Cassegrain. In these cases the amount of amplification introduced by the convex mirror is about $3\frac{1}{2}$ diameters (see p. 38); the equivalent focal length is therefore about $87\frac{1}{2}$ feet, and the ratio of aperture to focal length as 1 to $17\frac{1}{2}$. Fig. 24 shows the telescope as used for direct photography with the double-slide plate-carrier at the secondary focus. In Fig. 25 a spectrograph similar to the large Bruce spectrograph of the Yerkes Observatory is shown attached to the north side of the short cast-iron section of the tube; this affords a most stable base of support for the spectrograph, at a point where it can be easily counterpoised.

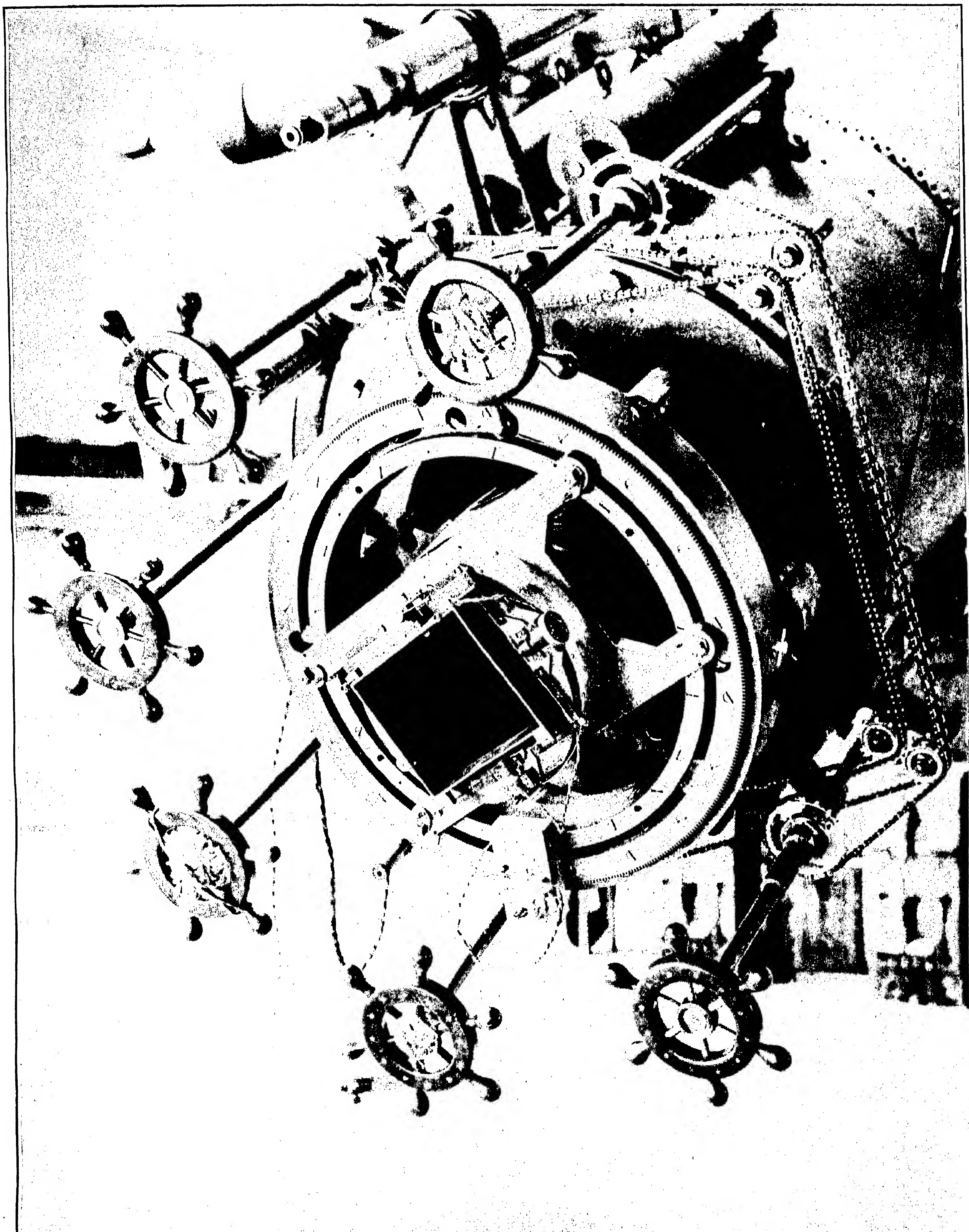
Figs. 26 and 27, Plate XII, illustrate the use of the telescope as a *coude;* the curvature of the convex mirror is now such that the equivalent focal length is about 125 feet. The cone of rays from the convex mirror strikes a diagonal plane mirror at the intersection of the polar and declination axes, and is by it reflected *in a constant direction*, which can be toward either the north or south pole of the heavens, as desired. This arrangement is almost indispensable when extremely large and powerful spectroscopes and other kinds of physical apparatus are to be used with the telescope; the focus is now in a constant position, so that such instruments need not be attached to the telescope, but can be mounted on stationary piers, in constant temperature rooms, if desired.

A brief description of the mechanism for quick-motion and slow-motion in right ascension and declination should be given. These are planned to be entirely electrical, although hand-motions are added, to be used in case of an emergency. Quick-motion in right ascension, both east and west, is given by the reversible motor *w;* this is connected by gearing to the large bevel-gear *x* through the medium of an electric clutch *y*. The bevel-gear *x* is permanently fixed to the polar axis. When the switch which starts the motor is thrown in, the electric clutch *y* acts, and a motion of rotation is communicated to the polar axis; this rotation is only at the rate of 45 degrees per minute; this is sufficient, since reversal is never necessary; hence very little power is required. The clutch is so adjusted that it will slip when even slight undue resistance is encountered. When the current is shut off from the motor the clutch is released automatically; the polar axis is then free from the motor and gear-train.

Quick-motion in declination is given in a manner entirely similar to that in right ascension, by a small reversible motor attached directly to the large cast-iron fork; this motor drives, through the media of a gear-train and an electric clutch, the toothed sector *z*, which is permanently fixed to the cast-iron section of the tube.

The driving-clock and 10-foot worm-wheel are "clamped in" to the polar axis, when desired, by the electric clamps *j* which lock the 10-foot worm-wheel to the bevel-gear *x;* the former is of course free to turn on the polar axis when not thus clamped.

Slow-motion in right ascension is given by means of a small reversible motor



LARGE DOUBLE-SLIDE PLATE-CARRIER ATTACHED TO 40-INCH REFRACTOR; YERKES OBSERVATORY.

which acts on a set of differential gears in the shafting connecting the driving-clock and the driving-worm. This device is used on the 2-foot reflector and on the 30-inch cœlostat, and is extremely simple and effective.

Slow-motion in declination is given by means of a small reversible motor which acts on the long sector attached to the upper trunnion shown in Fig. 22, Plate XII.

In concluding this necessarily brief and incomplete description of a modern reflector mounting, attention should be called to an attachment which is absolutely indispensable for the best results in direct photography of all celestial objects requiring long exposure. I refer to the double-slide plate-carrier, by means of which hand-guiding or correcting for the incessant small irregular movements of the image, which are nearly always visible in large telescopes, can be done incomparably more accurately and quickly than by any other means now known. This device is due to Dr. Common, who described it in *Monthly Notices*, Vol. 49, p. 297. In 1900 the writer designed and constructed a small attachment of this kind for use with the 40-inch refractor and the 2-foot reflector; this attachment and its use are described in the *Astrophysical Journal* for December 1900, p. 355.

The photograph of the central parts of the Andromeda Nebula (Plate I), was made by the writer with this small plate-carrier attached to the 2-foot reflector. The exposure time in this case was four hours. The images of the fainter stars on the original negative are only 2 seconds of arc in diameter; stars are shown which are more than a magnitude fainter than the faintest stars which can be detected visually with the 40-inch refractor; intricate structure and details are shown in the nebulosity, which are entirely invisible with the 40-inch refractor and all other visual instruments, and which have never been photographed before. When it is remembered that the focal length of the 2-foot reflector is only 93 inches, and that the aperture was in this case reduced to 18 inches, in order to secure a larger field than is well covered when the full aperture is used, some idea can be gained of the results which could now be obtained in celestial photography with a modern reflecting telescope which would compare in size, cost, and refinement of workmanship with the great modern refractors.

In Plate XIII is shown the large double-slide plate-carrier, taking 8 x 10 inch plates, which was constructed from the writer's designs in 1901, for use with the 40-inch refractor; the plate-carrier is here shown connected to the eye-end of the great telescope. A description of this attachment, together with some photographs obtained with it, will be found in the *Publications of the Yerkes Observatory*, Vol. II, p. 389.